LANGMUIR PROBE DIAGNOSTICS OF FLUCTUATION IN A REFLEX ARC NITROGEN PLASMA

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THESIS

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ABSTRACT

A reflex arc nitrogen plasma in a longitudinal magnetic field has been investigated by means of cylindrical Langmuir probes. Magnetic fields varying from 2400 gauss to 6600 gauss were studied. A radial profile of electron temperature and space potential was obtained as an aid to understanding the inner and outer rotational fluctuations previously noted to be characteristic of the reflex arc column. The effect of crossed magnetic and electric fields resulting in an $\vec{E} \times \vec{B}$ particle drift has been proposed as the primary mechanism of the outer rotational fluctuation, while the inner rotation mechanism has been proposed to be the $\vec{j} \times \vec{B}$ force of the magnetohydrostatic equation of a plasma in equilibrium. Diagnostic measurements of a theta pinch device on the plasma column were not successful due to circuit pick-up of electric signals due to the theta pinch current pulse.

TABLE OF CONTENTS

I. INTRODUCTION 11

II. THE PLASMA FACILITY 11

III. PLASMA FLUCTUATION STUDY 15

A. BACKGROUND 15

B. STUDY TECHNIQUES 15

C. CONDUCT AND RESULTS 18

1. Introduction 18

2. 60 Hz - 360 Hz Oscillation 18

3. Radio-Frequency Inner and Outer Oscillations 21

4. Plasma Profile Studies 27

D. INTERPRETATION OF RESULTS 45

1. Space Potential Study 45

2. Plasma Current Flow 46

3. Reflex Arc Oscillation Sources 48

4. Modification of Plasma Characteristics and Parameters 49

E. RECOMMENDATIONS 51

1. 60 Hz - 360 Hz Oscillation 51

2. Rotational Fluctuations 51

IV. THETA PINCH PERTURBATIONS 52

A. BACKGROUND 52

B. REFLEX ARC NITROGEN PLASMA 54

C. RECOMMENDATIONS 54

1. Plasma Facility 54

2. Measuring Devices 54

V. SUMMARY 55

BIBLIOGRAPHY 56

INITIAL DISTRIBUTION LIST 57

FORM DD 1473 59

LIST OF ILLUSTRATIONS

Figure		Page
1.	Top View of Plasma Facility	12
2.	Cathode-Anode Arrangement	14
3.	Theta Pinch Device	16
4.	Arrangement of Langmuir Probes Used to Confirm Rotational Direction of Oscillation	17
5.	Arrangement Used to Investigate 60 Hz - 360 Hz Oscillation	20
6.	Dummy Probe Oscilloscope Display with No Plasma and 2400 Gauss Magnetic Field	20
7.	Probe Circuit Used to Determine Direction of Rotation of Plasma Rotational Fluctuation	22
8.	Oscilloscope Display Reflecting Phase Difference of Rotational Fluctuations at Probe East and Probe Upper	22
9.	Outer Fluctuation Frequency as a Function of Radial Position and Magnetic Field	24
10.	Magnetic Field versus Outer Fluctuation Frequency as a Function of Radial Position	25
11.	Magnetic Field versus Rotational Frequency for Inner Fluctuation	26
12.	Langmuir Probe Circuit for Plasma Column Time Sampling	28
13.	Current - Voltage Characteristics of a Langmuir Probe	31
14.	Linear Extension of Ion Current Zone	31
15.	Probe Characteristic on a Semilogarithmic Scale	34
16.	Schematic of Time Sampling Triggering Technique	34
17.	Z-axis Modulated (upper) and Unmodulated (middle and lower) Current versus Sweep Voltage Characteristic Curve	37

Page

18. Time-Sampled Plasma Space Potential as a Function of Radial Position 37

19. Proposed Physical Mechanism of Rotational Fluctuation 39

20. Space Potential versus Radial Distance as a Function of Magnetic Field 41

21. Electron Temperature versus Radial Position as a Function of Magnetic Field 42

22. Electron Temperature versus Radial Position as a Function of Magnetic Field for Argon 44

23. A Cross-sectional View of Space Charge Distribution Responsible for Screw Instability of Positive Column 50

24. Theta Pinch Operation 53

LIST OF SYMBOLS

A	Region of saturation electron current
B	Transition region
$\vec{B}_o$	Longitudinal magnetic field in plasma column
C	Region of saturation ion current
e	Electron charge
E	Voltage
$\vec{E}_r$	Radial electric field
f	Frequency
i	Current
I	Current
I_e	Electron current
I_i	Ion current
I_o	Electron current in absence of retarding field
I_p	Probe current
$\vec{j}$	Current density
k	Boltzmann constant
r	Radius
R	Resistance
S	Slope
T_e	Electron temperature
U	Potential
v_d	Drift velocity
v_o	Azimuthal particle velocity

V	Potential
V_f	Floating potential
V_p	Probe voltage
V_s	Space potential
ρ	Mass density

ACKNOWLEDGEMENT

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I. INTRODUCTION

This work is an examination of the basic parameters of a reflex arc, magnetically confined, nitrogen plasma column produced in the plasma facility of the United States Naval Postgraduate School. Of particular interest were the turbulent nature of the plasma column and the modification of previously-measured parameters as a result of installation of a vacuum column constriction and a larger diffusion pump on the plasma facility. In addition, the effect of the newly installed theta pinch coil was to be investigated. Langmuir probe studies were conducted to determine the characteristics of the plasma fluctuations and to furnish parameters to aid in establishing a theoretical basis for the oscillations observed.

Langmuir probes and photomultiplier tubes were then to be used for plasma analysis during the application of the theta pinch and the expected theta pinch instigated instability period. The theta pinch device achieved operational status late in the period allotted for research and only a cursory look at the theta pinch effects was achieved.

II. THE PLASMA FACILITY

The plasma facility of the Naval Postgraduate School has been described in detail by Streit and Olsen [1] and Andrews [2]. The basic system, shown in Figure 1, consists of a four-inch diameter pyrex glass pipe connected to a high vacuum system capable of maintaining the

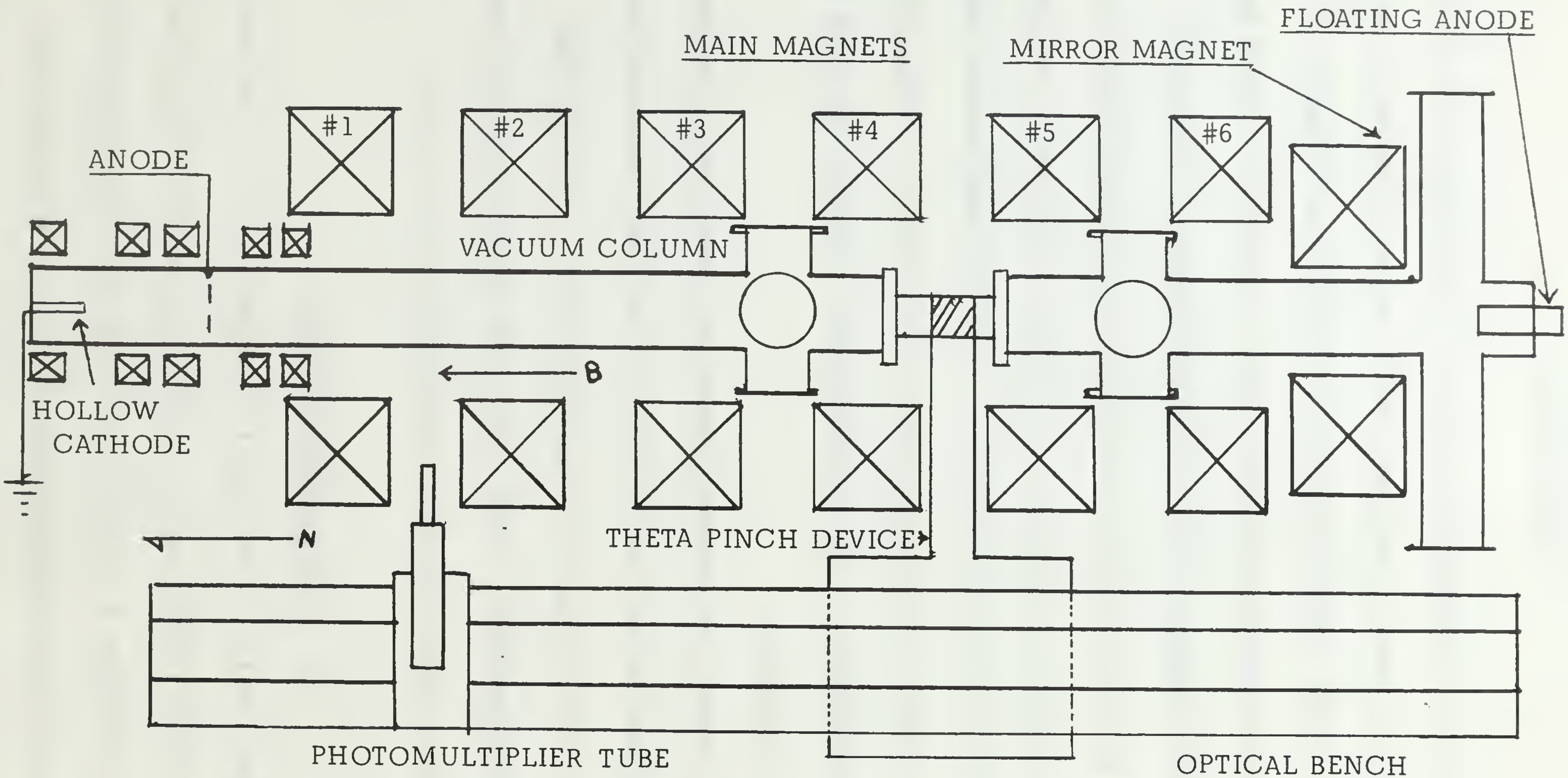


Figure 1. Top View of Plasma Facility

neutral gas pressure in the vicinity of 10^{-4} mm Hg while the system is in an operational state. The pyrex column is enclosed by six main magnet coils and a mirror magnet. Plasma-generating electrodes, a hollow cathode and annular anode, are located at the north end of the system and are contained in a complementary magnet system. The main magnet system is designed to produce a variable field up to 10,000 gauss which is homogeneous to within 2.5% along the axis of the plasma column.

The cathode-anode circuit is shown in Figure 2. A negative pressure gradient aids the flow of the nitrogen through the cathode toward the vacuum chamber. Electrons thermionically emitted from the inside wall of the cathode collide with and ionize a portion of the nitrogen flow. The pressure gradient as well as the potential gradient between the cathode and anode draw the electrons that have not returned to the cathode wall out of the cathode and toward the anode. A highly visible beam of plasma can be seen emerging from the cathode and passing through the hole in the anode. Once through the anode the nitrogen column is in the reflex arc configuration. The floating anode is insulated and serves only as an end point for the plasma column. In this experiment a 60 ampere cathode current was maintained. This current represents a cathode-anode current as the reflex arc column has no axial net current. Argon was used to start the arc and to establish the initial plasma beam. As the argon was turned off, nitrogen was fed into the gas supply. This operation is readily observable in the plasma column as a slow shift in color from the blue of argon to the pink of nitrogen.

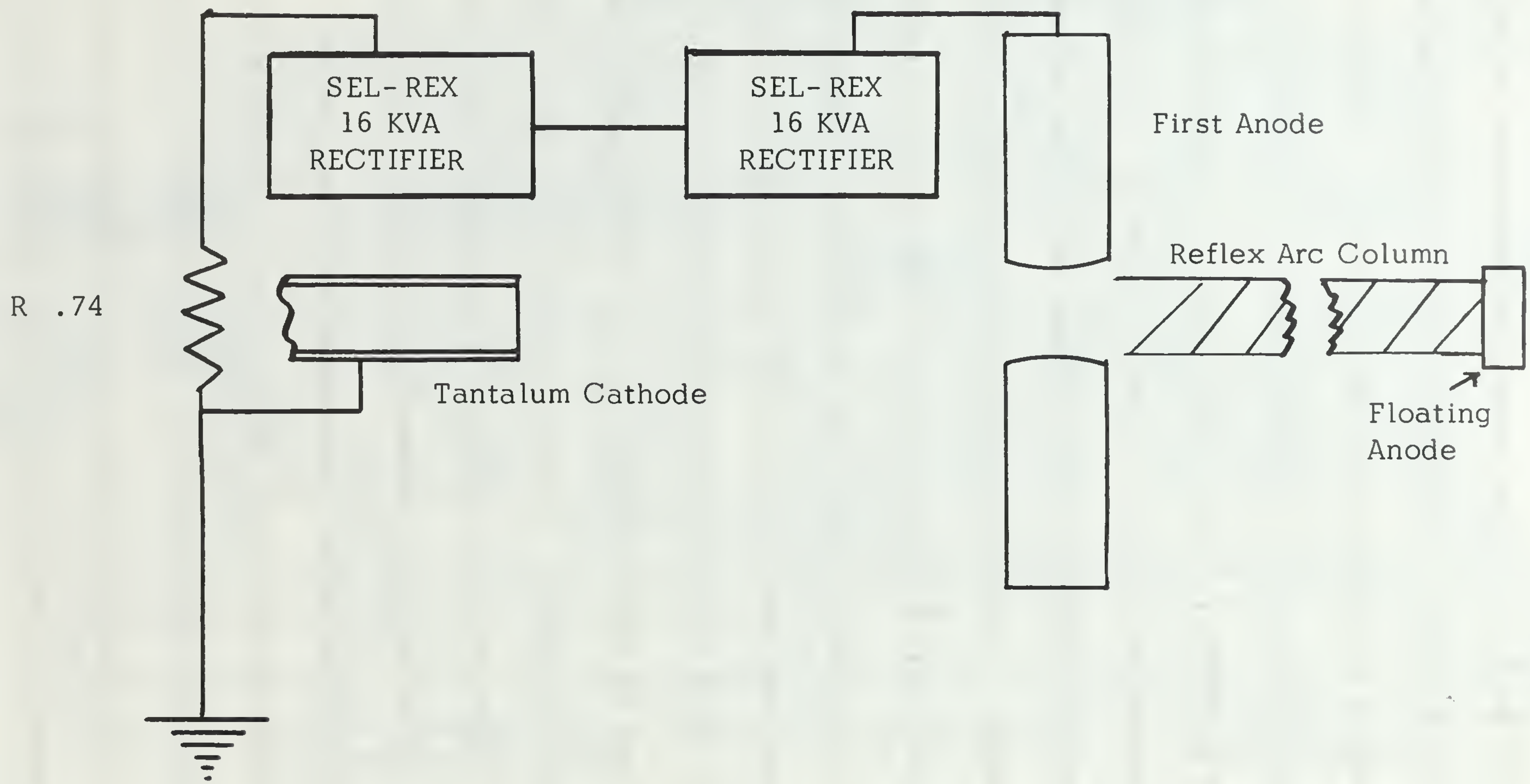


Figure 2. Cathode - Anode Arrangement

The recently completed theta pinch device has resulted in the installation of a 2-inch diameter constriction in the 4-inch diameter pyrex pipe. The theta pinch device consists of a 6-inch long single turn copper ring which fits around the 2-inch diameter pyrex glass constriction. The copper ring is connected in series with a 0.75 microfarad capacitor bank. The configuration of the theta pinch device is illustrated in Figure 3.

III. PLASMA FLUCTUATION STUDY

A. BACKGROUND

The plasma fluctuation studies were initiated with two objectives. The validity of the data obtained by Andrews [2] was to be re-examined in relation to the changes in the configuration of the plasma facility, and further studies were to be conducted into the characteristics of the plasma in order to interpret the initiation and propagation of the observed rotational oscillations.

B. STUDY TECHNIQUES

The techniques employed to confirm Andrews' findings used Langmuir probes, as opposed to Andrews' use of photomultiplier tubes. Figure 4 shows the Langmuir probe installation configuration. The probes were situated in the ports between main magnets #5 and #6. The probes consisted of .02 inch diameter tungsten wire, shielded over part of their length by a stainless steel tube. The tungsten wire directly in the plasma column was surrounded by alumina, which also served as an insulator inside the stainless steel tube. The projecting probe length

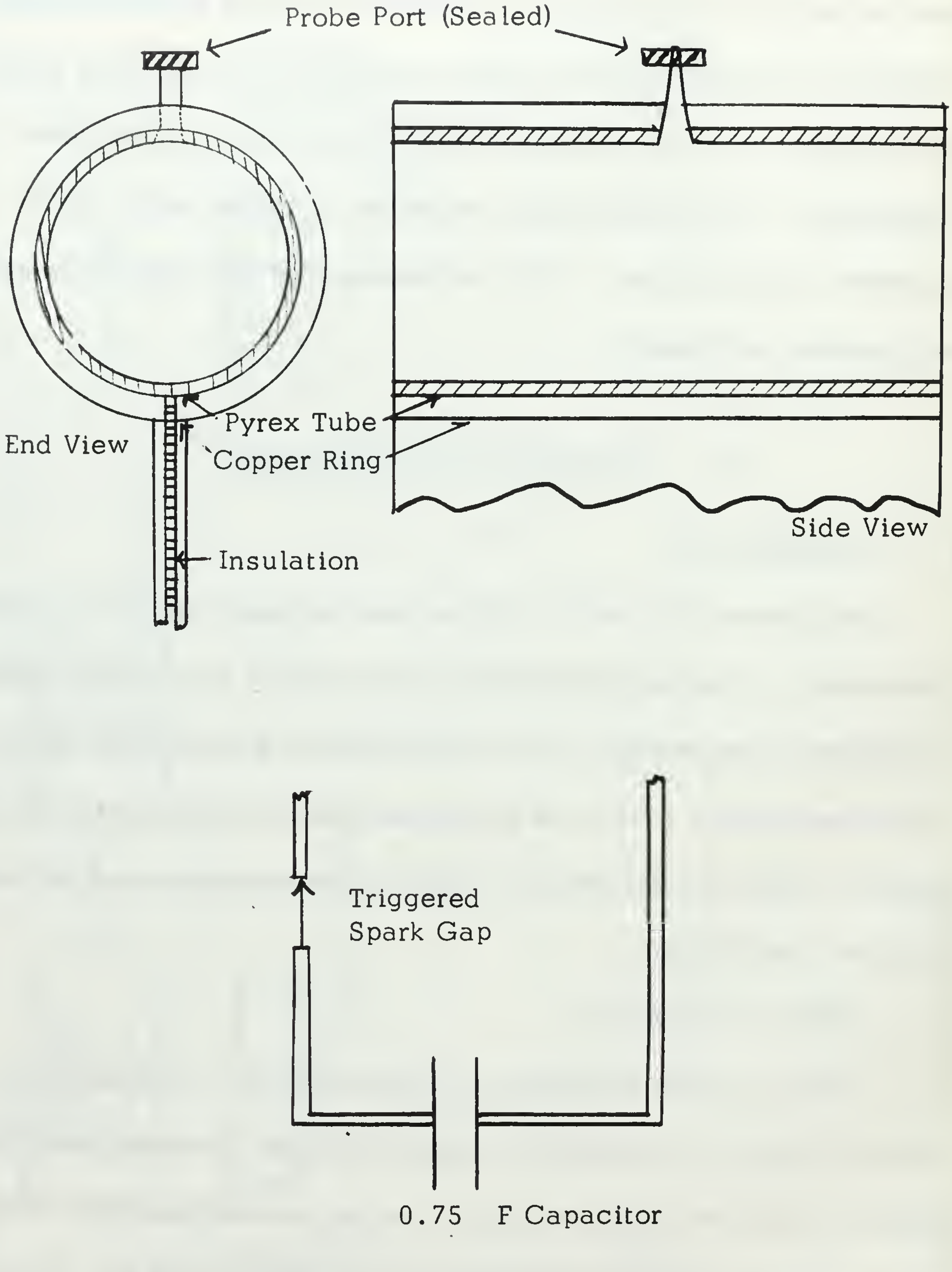


Figure 3. Theta Pinch Device

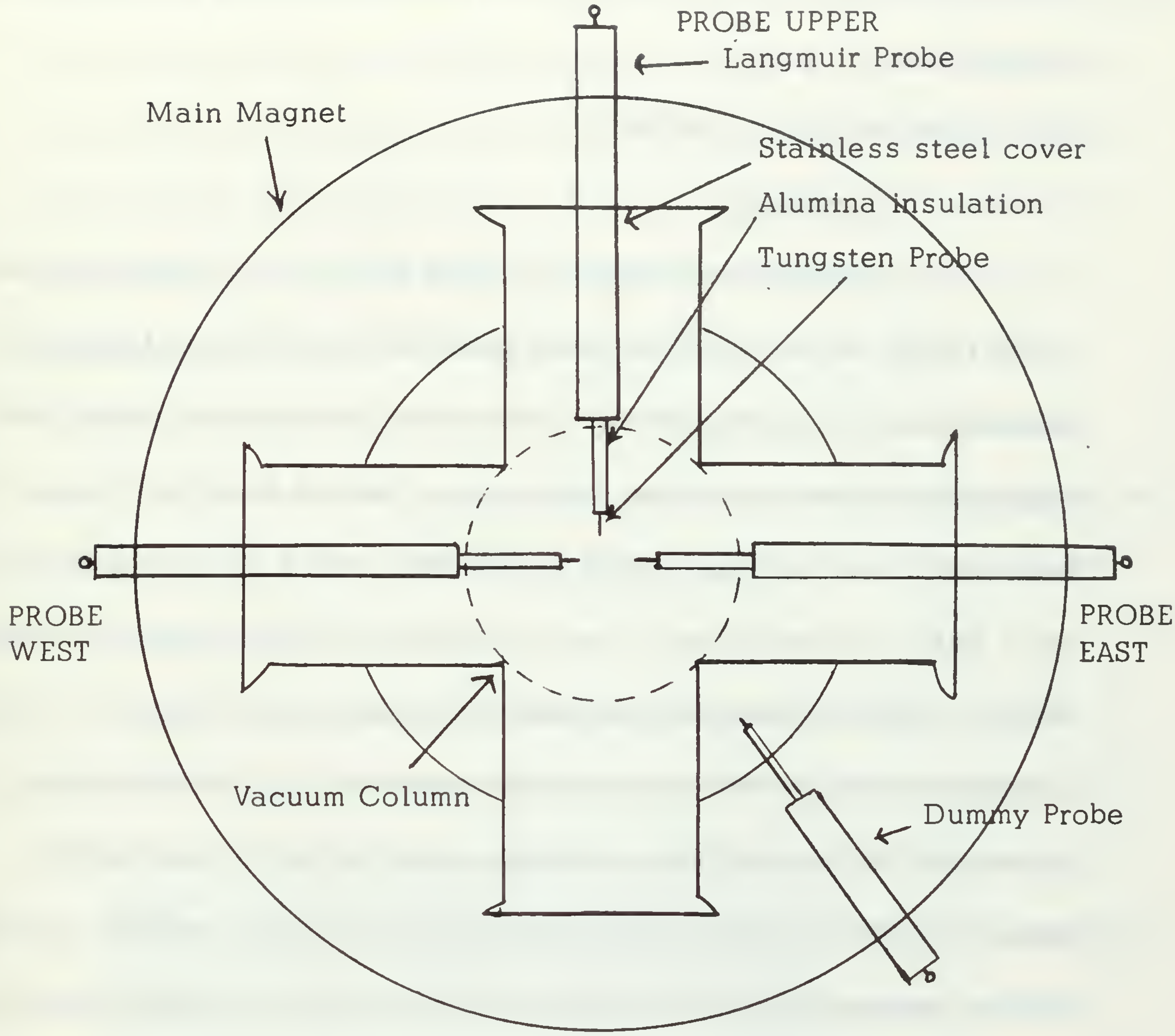


Figure 4. Arrangement of Langmuir Probes Used to Confirm Rotational Direction of Oscillation

of bare tungsten wire was 0.117 inches. A number of different circuits were necessary for the conduct of the investigation and will be discussed in the following section.

C. CONDUCT AND RESULTS

1. Introduction

Previous investigations of the plasma produced in the facility in the reflex arc configuration have revealed three dominant periodic fluctuations. Andrews, through photomultiplier analysis, found what appeared to be two rotational fluctuations, termed inner and outer, with frequencies ranging from 15 kHz to 400 kHz, and a 60 Hz-360 Hz fluctuation which did not appear to be associated with any particular plasma motion. The rotational oscillations were described as having a counterclockwise rotation when viewed from the cathode end of the plasma apparatus. It was the purpose of this investigation to confirm the presence of these fluctuations in view of the recently modified plasma facility parameters, and to obtain additional characteristics of the moving plasma column.

2. 60 Hz - 360 Hz Oscillation

The first approach to the 60 Hz - 360 Hz oscillation was to confirm the presence of the fluctuation while the plasma facility was in normal operation. The technique employed in this study was to allow the plasma column to reflect its fluctuation through a probe connected to ground through a 500 ohm resistance. Fluctuation in the plasma column was reflected as voltage variation across the 500 ohm resistor.

The arrangement shown in Figure 5, with the variable electronic filter adjusted to 400 Hz low pass, resulted in a 60 Hz sinusoidal oscilloscope trace with a 360 Hz signal riding upon the 60 Hz signal. The probe in the plasma and the dummy probe outside the pyrex tube displayed the trace in phase with one another. At this point, the dummy probe was moved from port to port toward the cathode end of the column with no phase shift being noted. The absence of a noticeable phase shift would show that the plasma column underwent the fluctuation at the same time along its entire length. It would have been difficult to detect wave propagation down the column if velocities were greater than 100 meters per second.

Two sources were considered likely candidates for the origin of this fluctuation; the cathode-anode arrangement and the magnetic field system, both of which are dependent on the public power system.

The second phase of the investigation was conducted to determine if the magnetic field system was responsible for at least a portion of the 60 Hz - 360 Hz fluctuation. The plasma facility was brought to full operating conditions, short of establishing the gas flow and plasma column, with a magnetic field of 2400 gauss. Figure 6 is the resulting dummy probe oscilloscope display using the circuit shown in Figure 5. The 60 Hz - 360 Hz oscillation was clearly visible on the oscilloscope display tube both for the dummy probe and the probe in the vacuum column. The large undulating signal of Figure 6 is a 60 Hz wave, while the smaller signal riding on the 60 Hz signal is a 360 Hz signal.

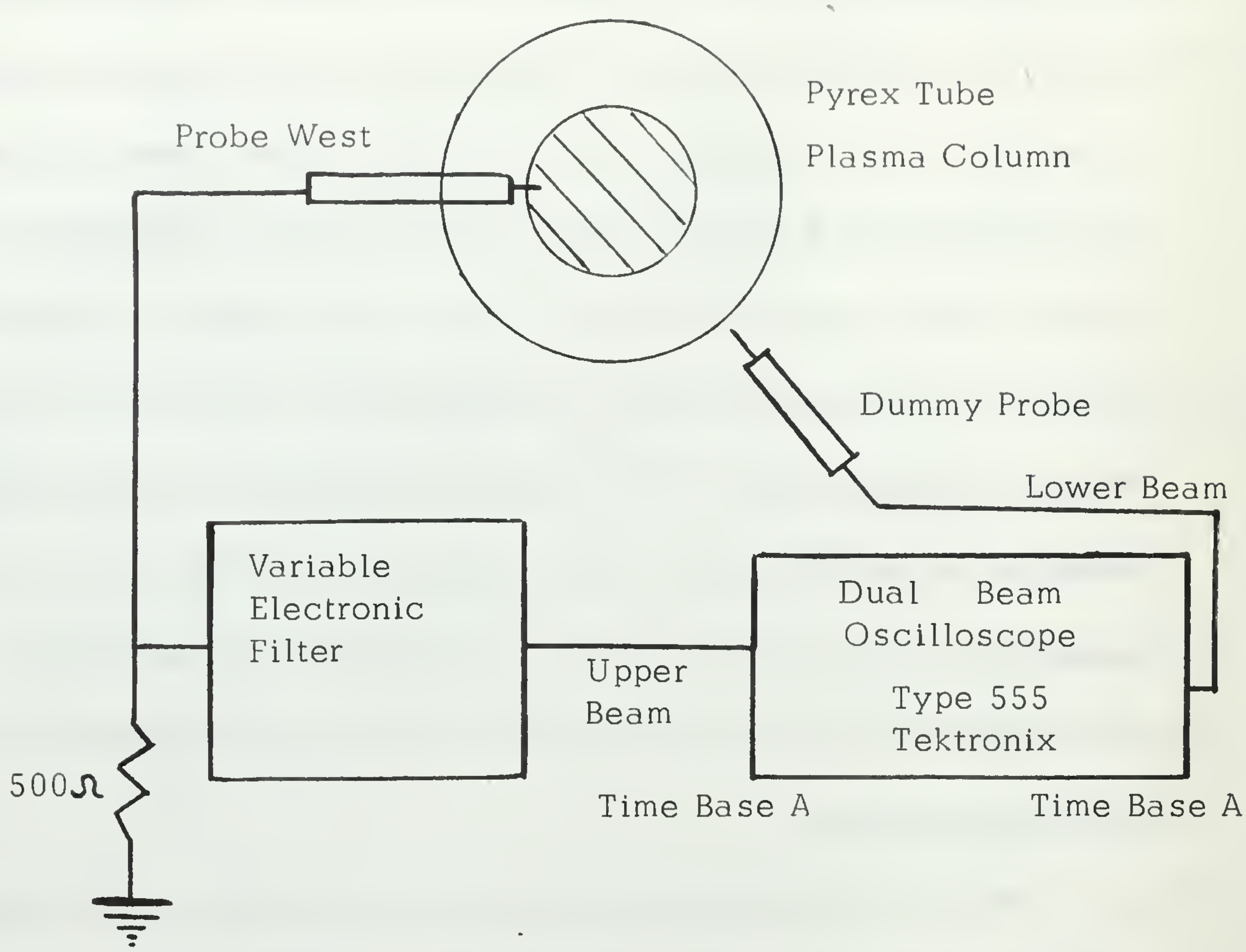


Figure 5. Arrangement used to investigate 60 Hz - 360 Hz oscillation

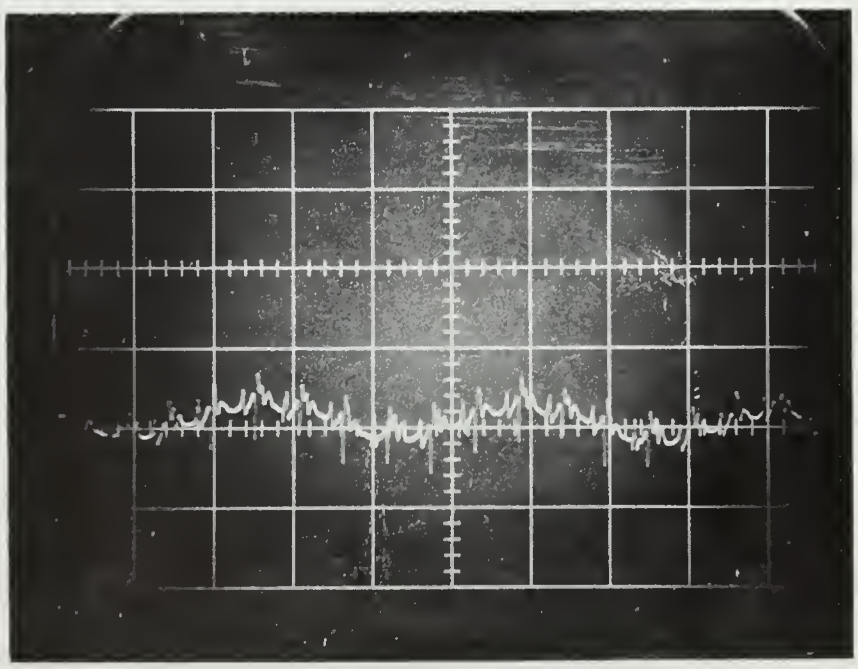


Figure 6. Dummy probe oscilloscope display with no plasma and 2400 Gauss magnetic field

The earlier photomultiplier tube studies conducted by Andrews show the presence of the 60 Hz - 360 Hz fluctuation in the light emission from the plasma column. This means that the fluctuation must be dealt with not only as an effect on the probes, which could be greatly reduced by using two probes with a differential amplifier, but also as an effect on the stability and characteristics of the plasma column.

Calculations of plasma facility circuit parameters have also implicated the cathode-anode complex in the 60 Hz - 360 Hz signal propagation, with the anode voltage variation being approximately 6% of the desired voltage setting.

The origin of this signal, presumably the public power system acting through the cathode-anode voltage and the magnetic field system, could possibly be better controlled through filtering, but for the present this does not appear to be a practical possibility, primarily because of financial considerations. As the 60 Hz - 360 Hz signal cannot now be eliminated, the present study will involve working with or through this signal.

3. Radio-Frequency Inner and Outer Oscillations

After initially determining that the previously observed inner and outer rotational oscillations could be registered on the Langmuir probes using the circuit shown in Figure 5, a study was made to confirm the direction of these rotations. The spaced probes as arranged in Figure 4 were used in conjunction with the circuit illustrated in Figure 7

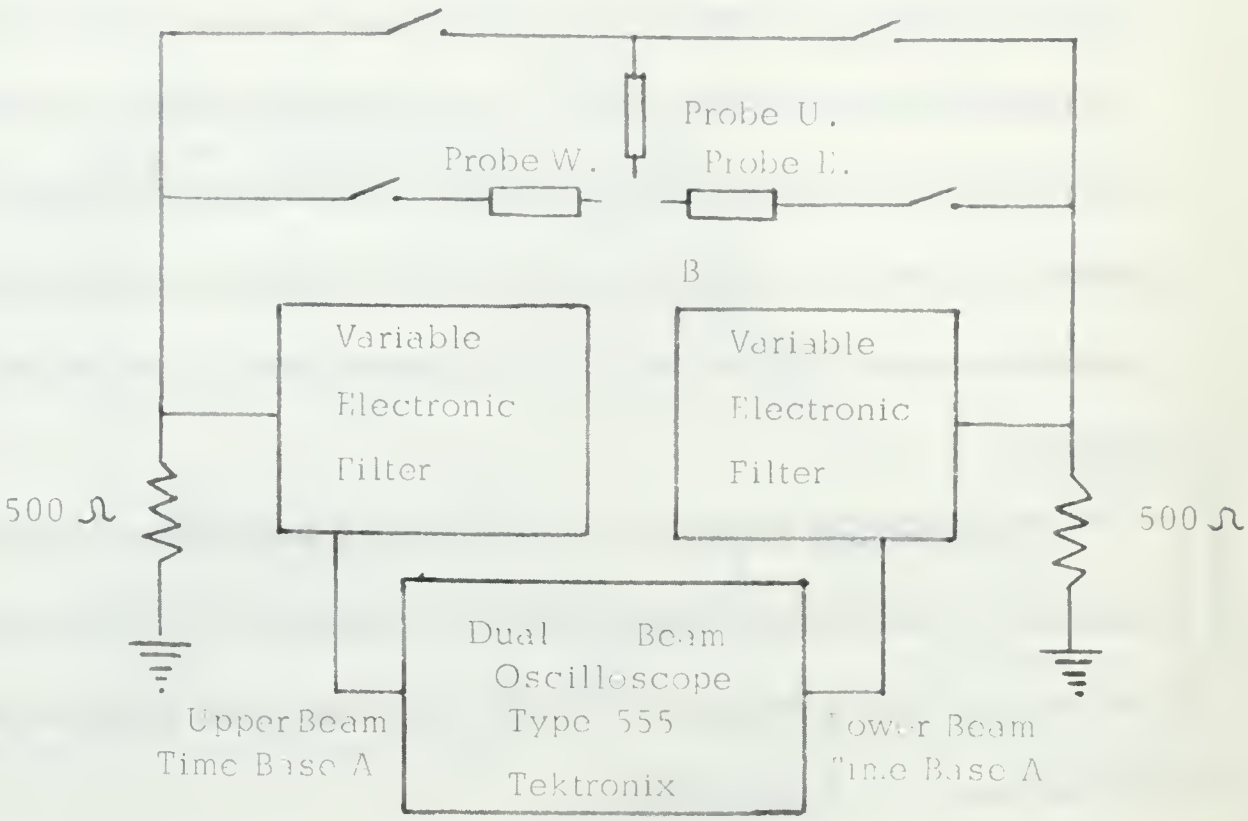


Figure 7. Probe Circuit Used to Determine Direction of Rotation of Plasma Rotational Fluctuation

Figure 8. Oscilloscope Display Reflecting Phase Difference of Rotational Fluctuation at Probe East and Probe Upper

to determine the direction of rotation. The periodic fluctuation of the plasma was observed as a voltage variation across the 500 ohm resistance in the probe circuit. The probes were positioned 3 cm from the center of the column and the phase relations of various probe combinations were examined. Figure 8, with probe east on upper beam and probe upper on lower beam, is an example of the dual beam oscilloscope displays obtained. Results of the investigation agree with the previous photomultiplier tube studies of Andrews. The rotational direction was found to be counterclockwise when viewed from the cathode end of the plasma column. Similar observations of the inner rotation at a radial distance of 0.5 cm also show a counterclockwise rotation when viewed from the same position.

Using the circuit of Figure 7, measurements were made at magnetic fields of 2400 gauss to 6600 gauss with the objective of establishing the plasma rotational frequency as a function of radial position. Once more the periodic plasma fluctuations were registered as voltage fluctuations across the 500 ohm resistance in the probe circuit. The results for the outer mode are shown in Figures 9 and 10 and for the inner mode in Figure 11.

The outer or slow rotation demonstrates two macroscopic properties of interest, other than the actual rotational velocities. As a general rule, for any given radial position within the plasma column, the frequency of rotation increased as the magnetic field increased. At the highest magnetic field examined, radial positions 1.0 cm and 2.5 cm

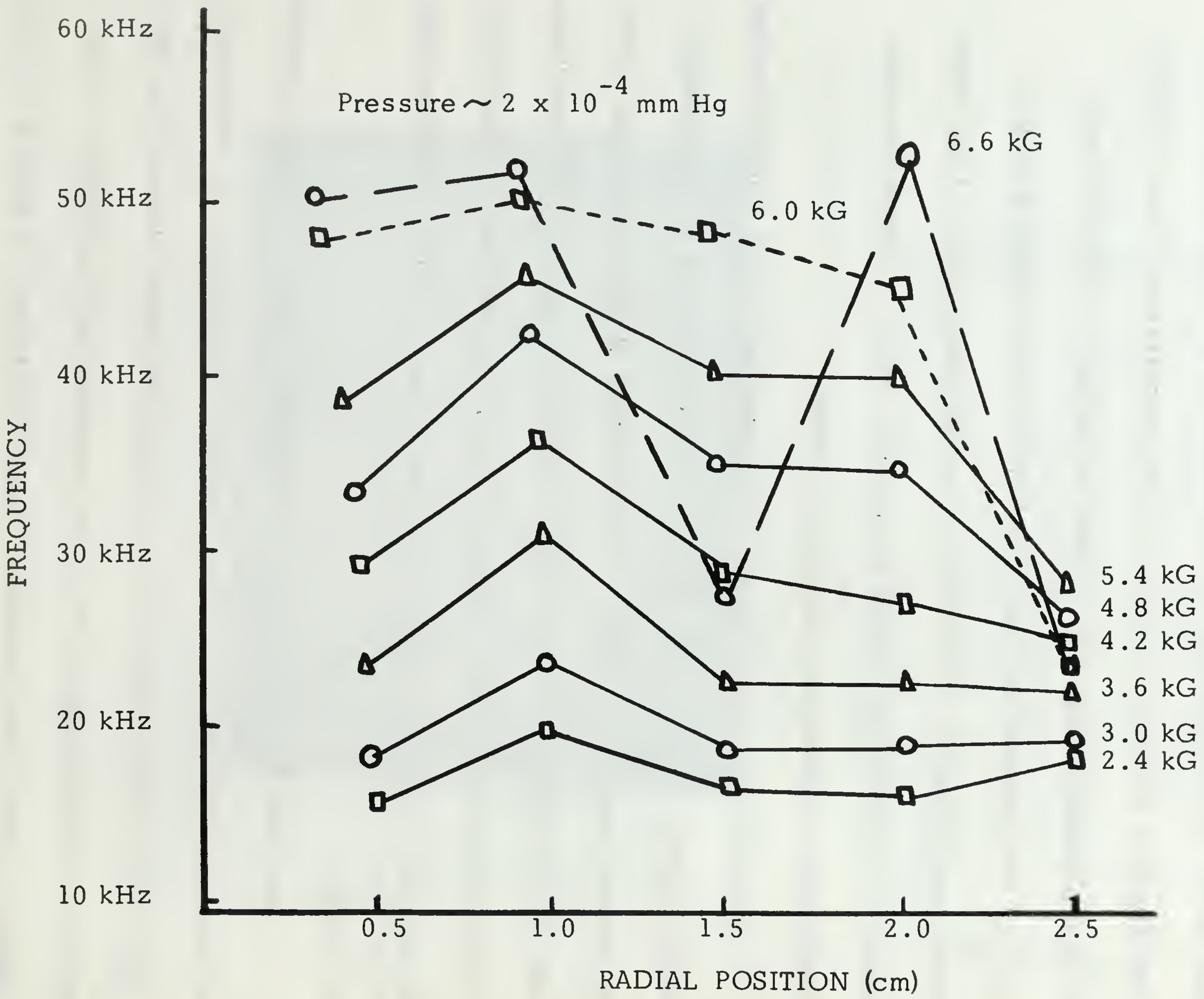


Figure 9. Outer Fluctuation Frequency as a Function of Radial Position and Magnetic Field

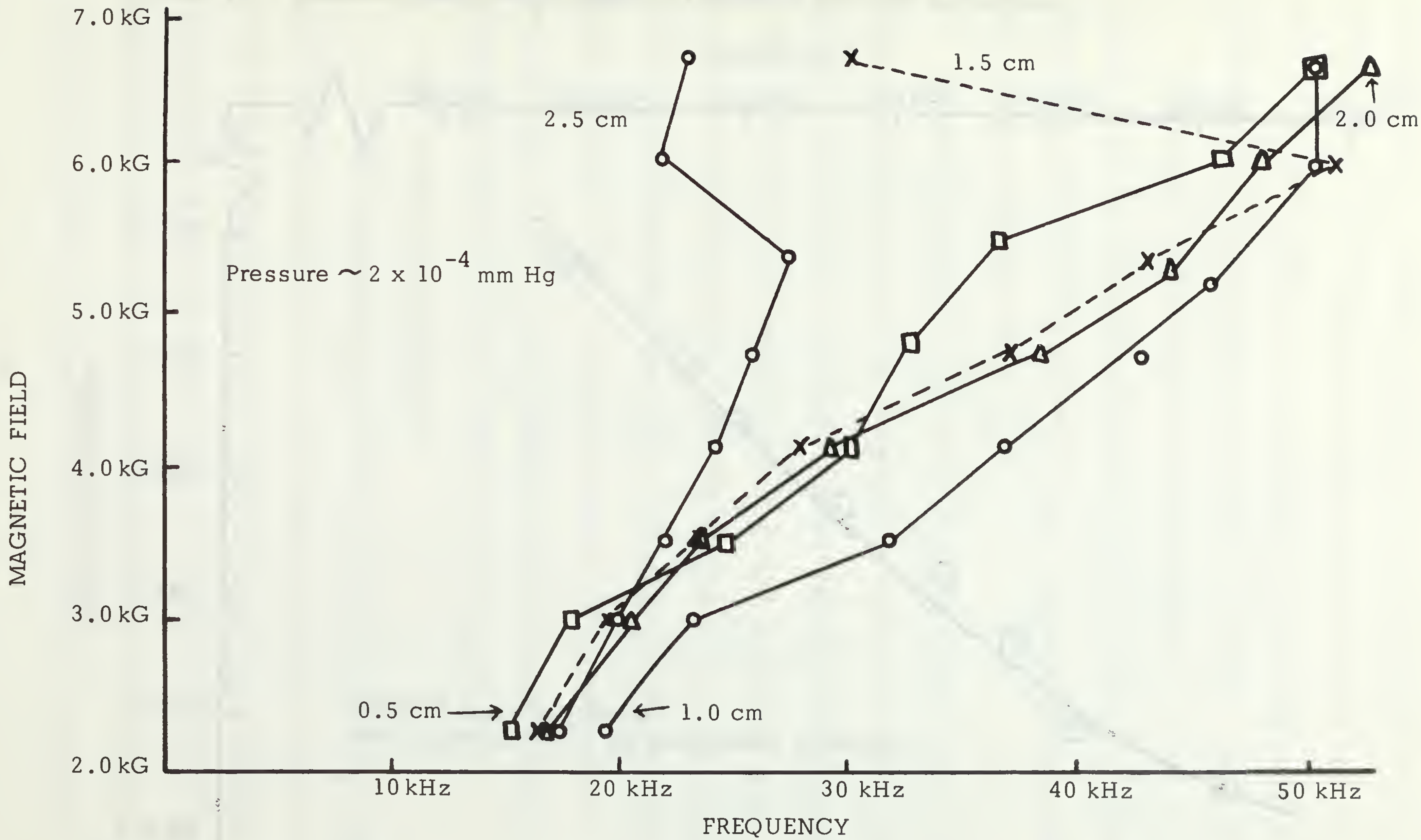


Figure 10. Magnetic Field versus Outer Fluctuation Frequency as a Function of Radial Position

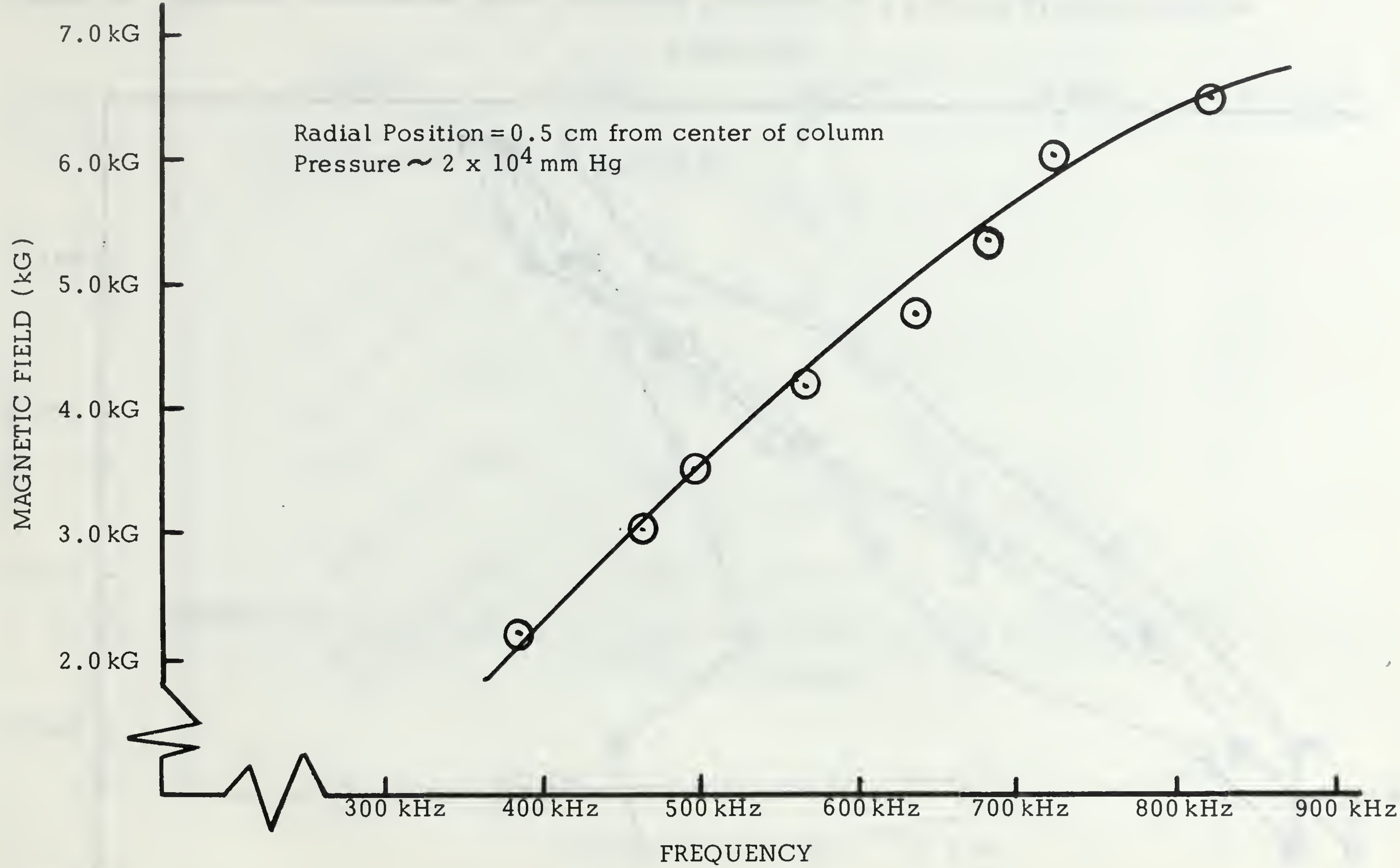


Figure 11. Magnetic Field versus Rotation Frequency for Inner Fluctuation

violated this rule. A greater rotational velocity was found at the 1.0 cm radial position for all except the highest magnetic field investigated. These results are elements in the explanation of the propagation of the fluctuation and will be explored more fully in section III, paragraph D.

The inner or fast oscillation was not observed at a radial position greater than 0.5 cm from column center. Figure 11 shows a nearly linear relationship between frequency and magnetic field over the range measured, with a slight deviation at 6600 gauss.

Though the terms inner and outer have been applied to the rotations, Langmuir probes registered both phenomena at the 0.5 cm radial position, thus making it difficult to establish separate zones for the oscillations, if such zones exist. Movement of the probe into the column center resulted in increased random voltage fluctuations in the probe circuit, but outer oscillations were still noted. The outer and inner oscillations overlap within the center of the plasma column according to probe measurements. The 0.117 inch long probe may have been extending through two different oscillation zones of the plasma column.

4. Plasma Profile Studies

An investigation of the plasma column in profile was undertaken to form a foundation for possible mathematical treatment of the plasma fluctuations. Studies were conducted using a time sampling system similar to that used by Hart [3], the objective being to measure the plasma parameters with a Langmuir probe during specific phases of the plasma oscillation. The circuit shown in Figure 12 was used to

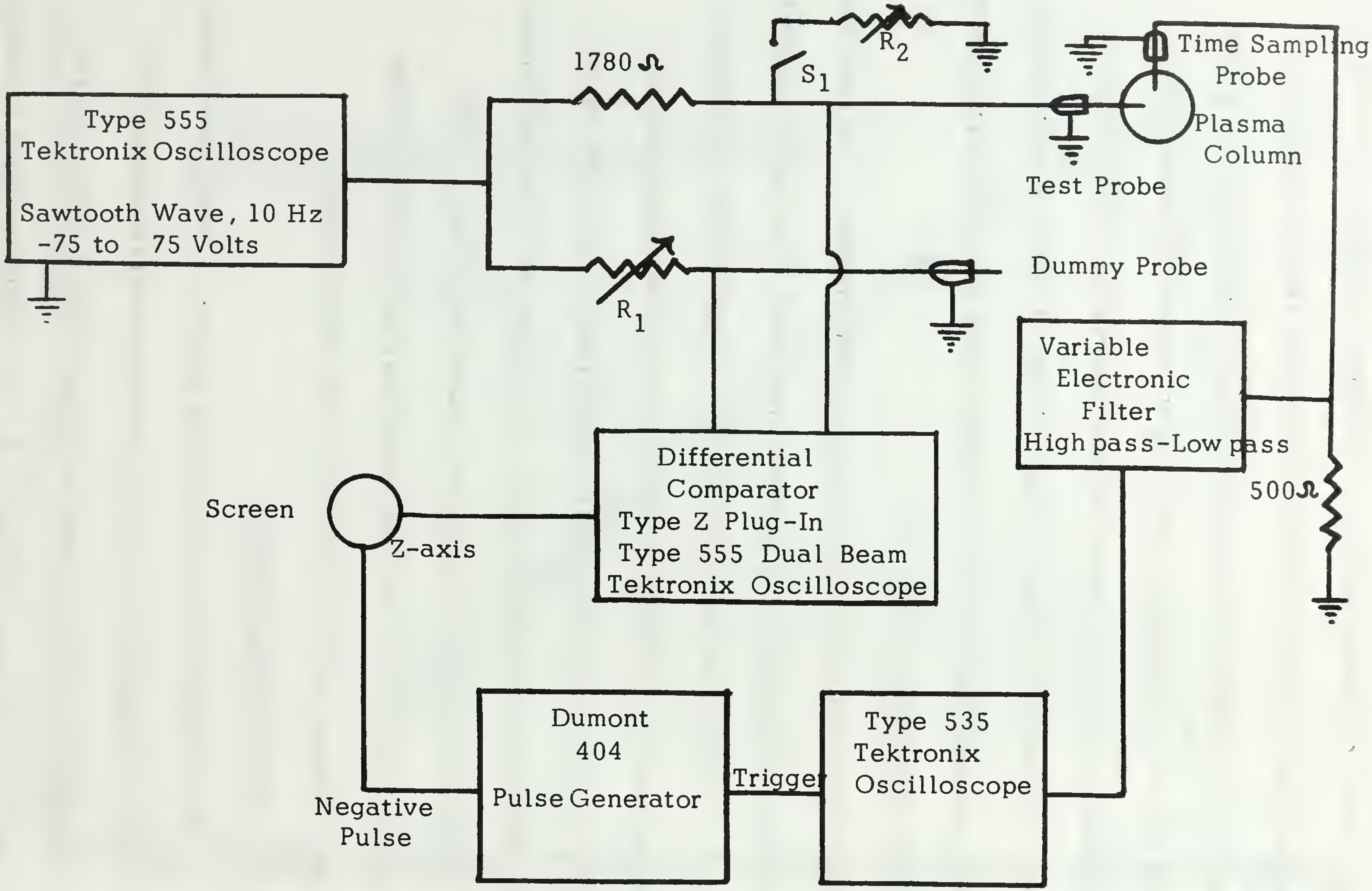


Figure 12. Langmuir Probe Circuit for Plasma Column Time Sampling

conduct this portion of the investigation. A -75 to +75 volt, 10 Hz sawtooth wave was impressed on the circuit as shown. Prior to the initiation of the plasma column, the resistance R_1 was adjusted so that a horizontal oscilloscope trace was obtained. Switch S_1 was closed only for testing the system, with resistance R_2 serving as the test probe. The dummy probe was placed adjacent to the vacuum column and test probe. Signals from the test probe and the dummy probe were passed into the differential comparator in the type 555 Tektronix dual beam oscilloscope where stray signals were removed and which passed on to the oscilloscope display tube the voltage differences between the test probe and the dummy probe. The x-axis of the oscilloscope trace is a direct display of the sweep voltage, -75 volts to +75 volts. The oscilloscope trace y-axis deflection amplitude is due to the voltage difference between the test probe and dummy probe. As the circuit diagram illustrates, the -75 volt to +75 volt sawtooth wave is impressed on both the test probe and dummy probe circuits at the same instant. As the dummy probe circuit has no path to ground except via the sawtooth wave circuit and the differential amplifier, the dummy probe will assume the instantaneous potential of the sawtooth wave and no current will flow in the circuit. The test probe has a path to ground via the plasma and a current will flow through the 1780 ohm resistor. The vertical amplitude of the oscilloscope display represents the voltage difference between the dummy probe and the test probe due to the

potential drop IR in the probe resistor and can in turn be related to the current in the test probe circuit through the formula:

$$E = I\,R$$

$$R = 1780 \text{ ohms}$$

$$I_{\text{Test Probe}} = \frac{E_{\text{Vertical}}}{1780 \text{ ohms}} \text{ amperes}$$

The voltage drop across the 1780 ohm resistance is so slight that for measurement purposes the instantaneous sawtooth wave voltage may be assumed to be the test probe voltage along the x-axis of the oscilloscope trace. The oscilloscope display is the probe characteristic curve of Langmuir's theory.

F. F. Chen [4] offers a comprehensive review of the theory of the characteristic curve as shown in Figure 13. The following characteristics apply to the labels used in Figure 13;

i	=	Current to Probe
V_P	=	Probe Voltage
V_s	=	Space Potential (Probe same potential as plasma)
A	=	Region of Saturation Electron Current
B	=	Transition Region or Retarding Field Region
C	=	Region of Saturation Ion Current
V_f	=	Floating Potential (Probe sufficiently negative to repel all electrons except a flux equal to the flux of ions)

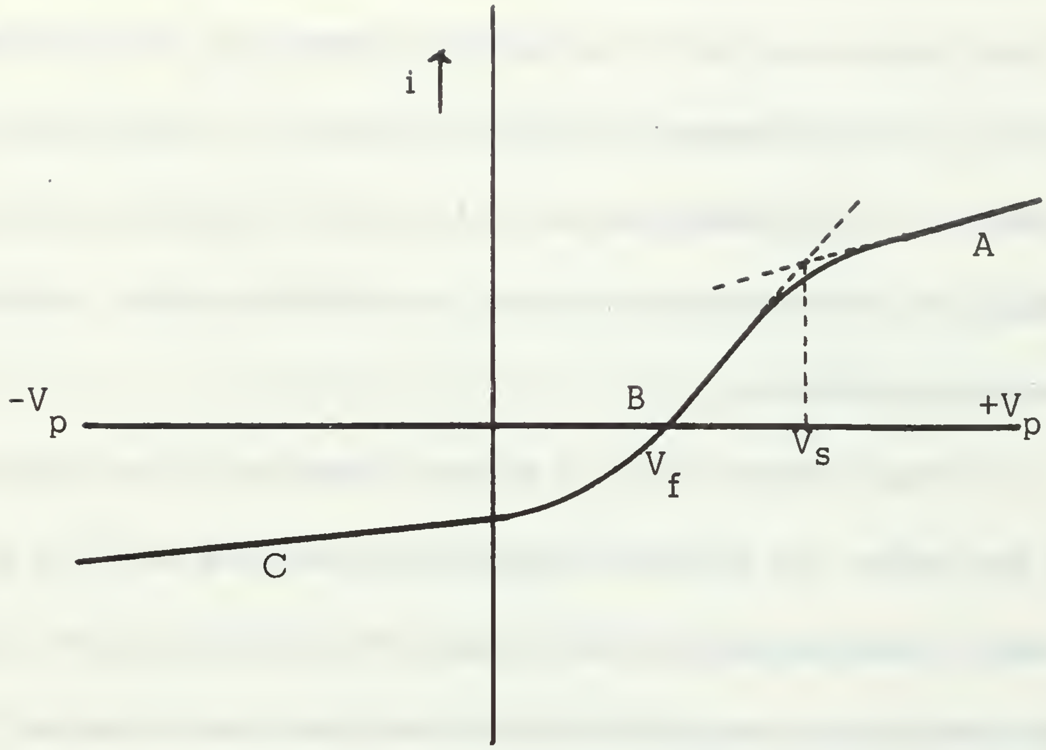


Figure 13. Current-Voltage Characteristics of a Langmuir Probe

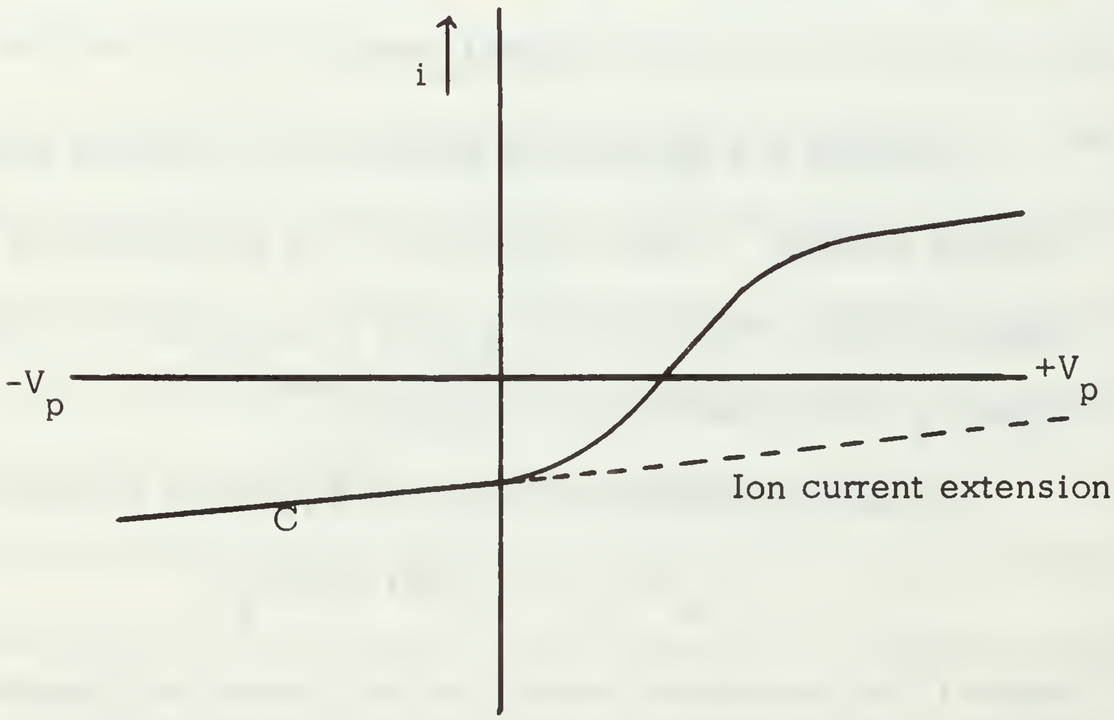


Figure 14. Linear Extension of Ion Current Zone

The voltage applied to the probe is plotted along the x-axis and the current flowing through the probe circuit is plotted along the y-axis. If the voltage applied to the probe is increased, three different parts of the probe characteristic will be traversed. In the region marked A in Figure 13, the current flowing to the probe is due to positive ions. Region B shows a rapid increase in electron current, which in region C reaches saturation.

When a large negative voltage, relative to the plasma, is applied to the probe, the current is due to positive ions only, as the electrons cannot reach the probe. As the probe potential becomes less negative, the electrons in the tail of the Maxwellian distribution will begin to penetrate to the probe.

A relation between the probe current (I_p), ion current (I_i), and electron current (I_e) can be written:

$$I_p = I_e + I_i$$

In region B a Maxwellian distribution of electron energies is assumed to exist. If this is the case, then the fraction of the total electron current which reaches a probe at potential V is $\exp(-eV/kT_e)$ where T_e is the electron temperature.

The general expression for the probe current in region B becomes:

$$I_p = I_i + I_o \exp(-eV/kT_e)$$

where I_o is the electron current in the absence of a retarding field. Subtracting the ion current, the electron current is obtained.

$$I_p - I_i = I_e = I_o \exp(-e V / v T_e)$$

Further manipulation yields

$$\ln I_e = \ln I_o - (e V / k T_e).$$

Thus, assuming the ion current decreases smoothly as the voltage becomes less negative, the electron current, calculated by subtracting the ion current (Region C) and its linear extensions from the measured probe current, can be plotted on a semilogarithmic scale versus the probe potential, as illustrated in Figures 14 and 15. The slope S on Figure 15 is equal to the value $(e / k T_e)$. Knowing the slope of the graph, the electron temperature can be determined.

The present study is concerned with the characteristics of the rotating plasma. The above described procedure presupposes the plasma remaining somewhat stable within the vicinity of the probe for at least the time of the voltage sweep. Two measuring methods seem to offer possibilities of overcoming the obstacle of a time dependent plasma. The first method would involve an extremely rapid voltage sweep of the probe. This method was not attempted for a number of reasons. Crude calculations reveal that to sweep during 1/20 of one cycle of a 30 kHz rotation would require a 1.6 μsec voltage sweep. A sweep of this speed would involve network impedance to a much greater extent than sweeps in the Hertz range. In addition, a study of pulsed probes by Bills, et al [5] has shown that field-induced ion movement through a probe sheath may take as long as 1 microsecond. Most important, a sawtooth voltage sweep in the MHz range was not available with the voltage range desired. Initially, a 202A function generator was employed to furnish a triangular

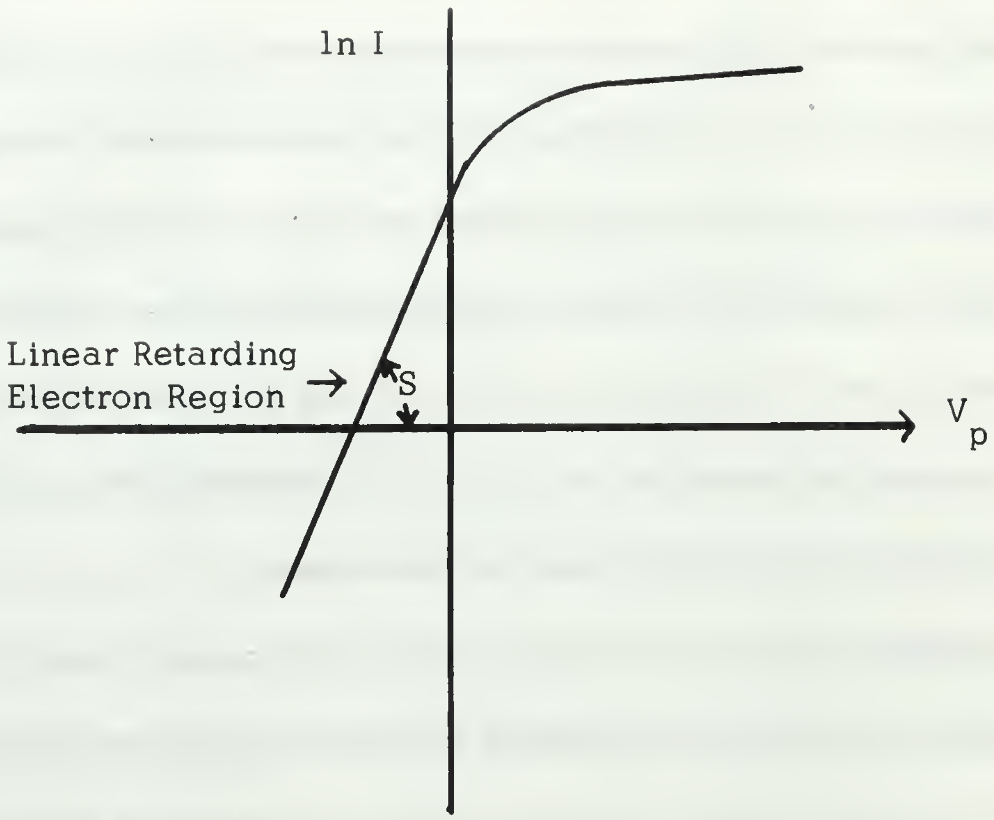


Figure 15. Probe Characteristic on a Semilogarithmic Scale

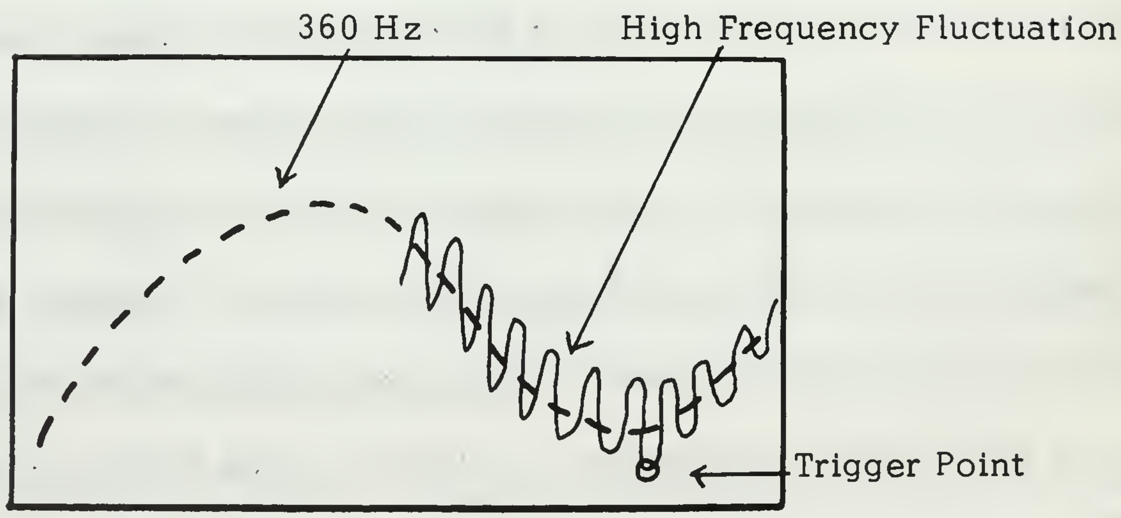


Figure 16. Schematic of Time Sampling Triggering Technique

wave, but the -18 volts to +18 volts maximum amplitude was found to be inadequate for the voltage characteristics of the plasma column. A definite ion current region was not visible under certain plasma conditions. This region was necessary for proper interpretation of the characteristic curve. The space potential of some regions of the plasma column was found to exceed 18 volts.

The method adopted involved time sampling techniques similar to those employed by Hart, as mentioned earlier. The method employs the plasma oscillation as a trigger for a pulse which in turn modulates the intensity of the oscilloscope beam, thus recording the characteristic curve only when the periodic plasma fluctuation is at a specific stage. The sampling probe of Figure 12 and the illustrated circuit were used for this purpose. As an aid to sampling, the trigger pulse could be delayed for a specific variable time so that various points of the oscillation cycle could be sampled. A schematic of the wave form seen by the time-sampling probe is shown in Figure 16. The radio-frequency oscillation superimposed on the 360 Hz fluctuation was used to obtain the triggering point. The point was selected at the minimum vertical displacement of the trace because of the better definition of the trace at that point.

The probe sawtooth voltage sweep rate used was 10 Hz, which would result in 36 oscilloscope beam modulations per sawtooth sweep if the triggering took place once at the minimum vertical point of the 360 Hz signal. The results of this technique offered a substantial

improvement in data resolution over the unmodulated probe characteristic curve. Figure 17 illustrates the effect of beam modulation, the lower two sweeps being unmodulated traces, and the upper display of dots being an unrelated time sampled sweep.

Using the time sampling technique as illustrated in Figure 12, a radial analysis of the reflex arc plasma column was conducted from column center to a 5.0 cm radius, with fields of 2400, 3600, 4200, and 4800 gauss. Anode voltage was in the order of 70 volts and the cathode was grounded. The cathode-anode current was maintained at 60 amperes. Neutral gas pressure varied somewhat, with an attempt being made to obtain lowest possible background gas pressure at all times. The neutral gas pressure, as measured with an ion gauge, was generally in the vicinity of 10^{-4} mm Hg.

The Langmuir probe characteristic curves were first analyzed for the space potential of the plasma column. The space potential versus delay values as obtained from polaroid photographs of the time sampled traces for a magnetic field of 2400 gauss are illustrated in Figure 18. At the radial distance of 0.5 cm, the time-sampling probe was unable to perform its function because of the presence of random fluctuations in the plasma at that point. As a result, the space potential for that position was obtained from a series of unmodulated traces.

The periodicity of the space potential agrees with the earlier findings of periodic rotation of a portion of the plasma column. Too strict a value must not be attached to the apparent time of oscillation

Figure 17. Z-axis Modulated (upper) and Unmodulated (middle and lower) Current versus Sweep Voltage Characteristic Curve

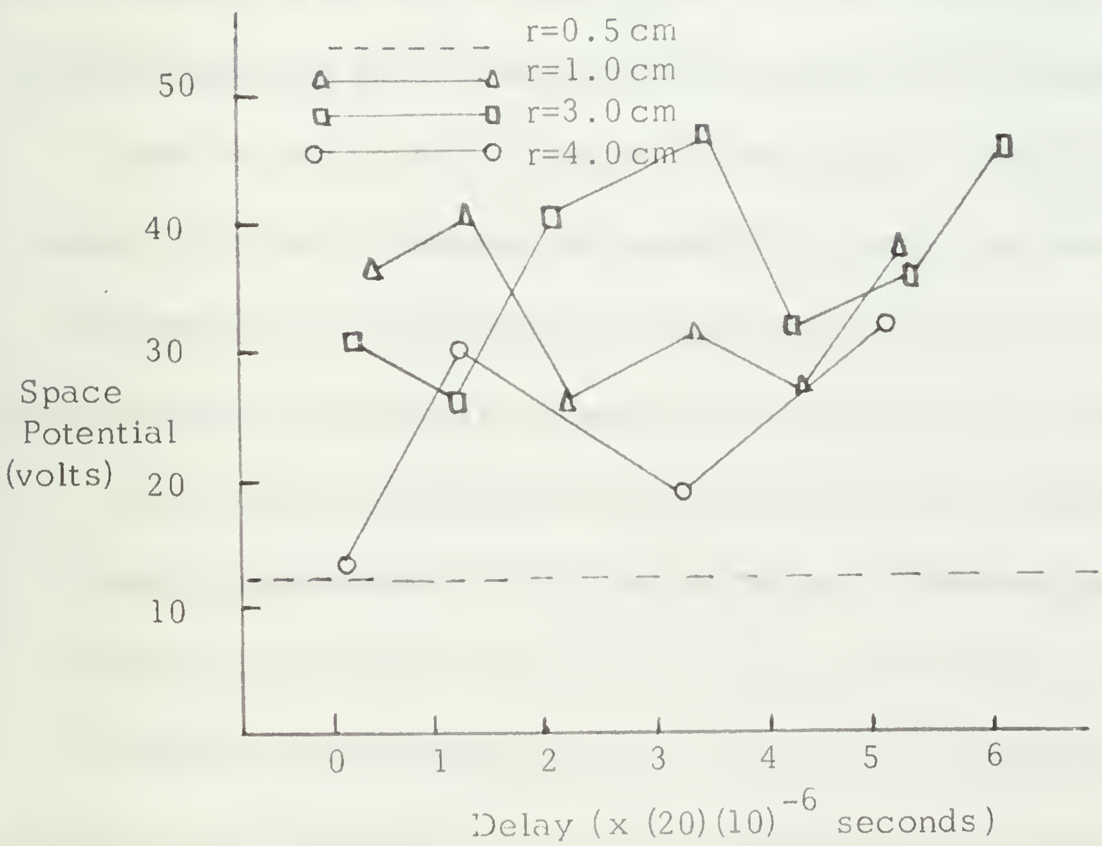


Figure 18. Time-Sampled Plasma Space Potential as a Function of Radial Position

as reflected in Figure 18, as the readings noted were taken only at specific delay intervals, with the lines between points being added for clarity only. Missing points cannot readily be deciphered from the photographs and points for R = 1.5 cm and R = 2.0 cm have been deleted from Figure 18 for clarity.

A compilation of data, similar to that illustrated above, was made for the reflex arc column in magnetic fields of 2400, 3600, 4200, and 4800 gauss. The rotational oscillation study showed that different radial positions in the plasma column reflected differing oscillation frequencies. This situation would allow the averaging of space potential variations found for any particular radial position if it was found desirable to treat a particular radial position as having a specific space potential. The time sampled space potential measurements showed a time dependent space potential variation which would indicate a local azimuthal electric field and a variation of space charge density in the plasma column.

A proposed mechanism illustrating the apparent situation is shown in Figure 19. It is difficult to compare this model with a macroscopic physical system as the rotating shells are not azimuthally symmetric with respect to charge. The periodicity of the phenomena at each radial position allows the meaning of the word shell to be stretched slightly to include the varied plasma parameters found at each radial position. Cylindrical symmetry is not implied. When consideration is given to the radial dependent azimuthal drift velocities, reference to an azimuthal electric field becomes meaningless, as in effect there would be a series

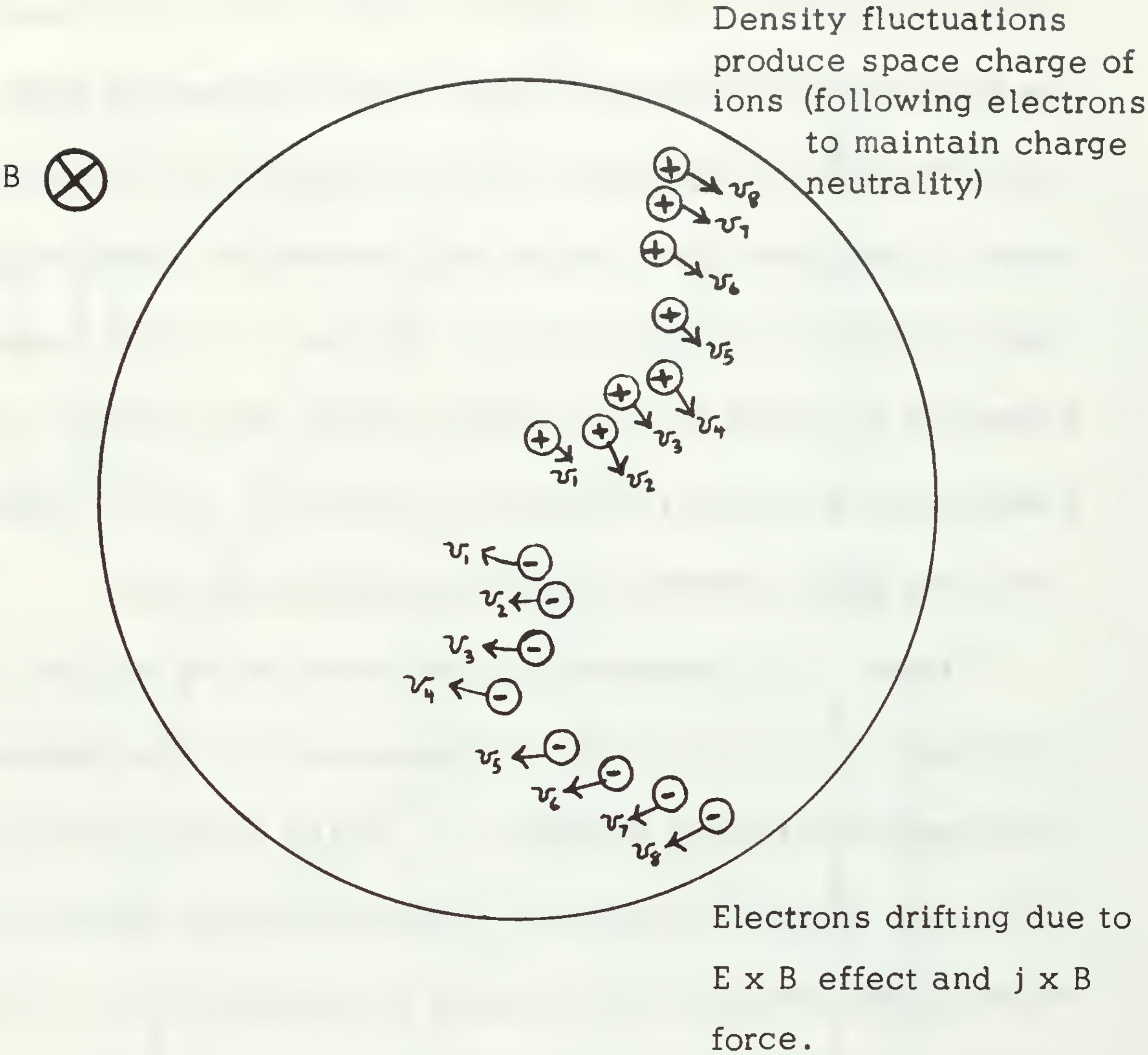


Figure 19. Proposed Physical Mechanism of Rotational Fluctuation

of random, ever changing, radius-dependent azimuthal electric fields. A further hypothesis in explanation of the time dependent space potential variation would assign the establishment and propagation of the rotational oscillation to a space-charge-dependent effect, independent of the effect of the sign of particle charge, with the electrons by virtue of their light mass leading the heavier ions which would have a larger frictional force with which to contend. The time dependent space potentials measured for each radial position were averaged to obtain an average space potential for the radial position. This allowed comparison of the space potentials at various radial positions.

Figure 20 is a graphical representation of the results of this comparison. The graph shows the presence of a radial electric field $\vec{E}_r$. As the magnetic field is increased, $\vec{E}_r$ in the vicinity of the column center also appears to increase. Experimental results show that the column center remains in the vicinity of ground potential. This result would be expected, as the cathode remains at ground. The interior of the plasma column could be assumed to be fairly well shielded from the anode and would act as an extension of the cathode.

The electron temperature distribution as obtained from the characteristic curves is shown in Figure 21. The point at 3600 gauss and 2.5 cm appears to be inconsistent when compared with the majority of the data. The electron temperatures indicated appear to be somewhat higher than the electron temperatures obtained by Cote [6] using spectroscopic techniques, Cote's values being;

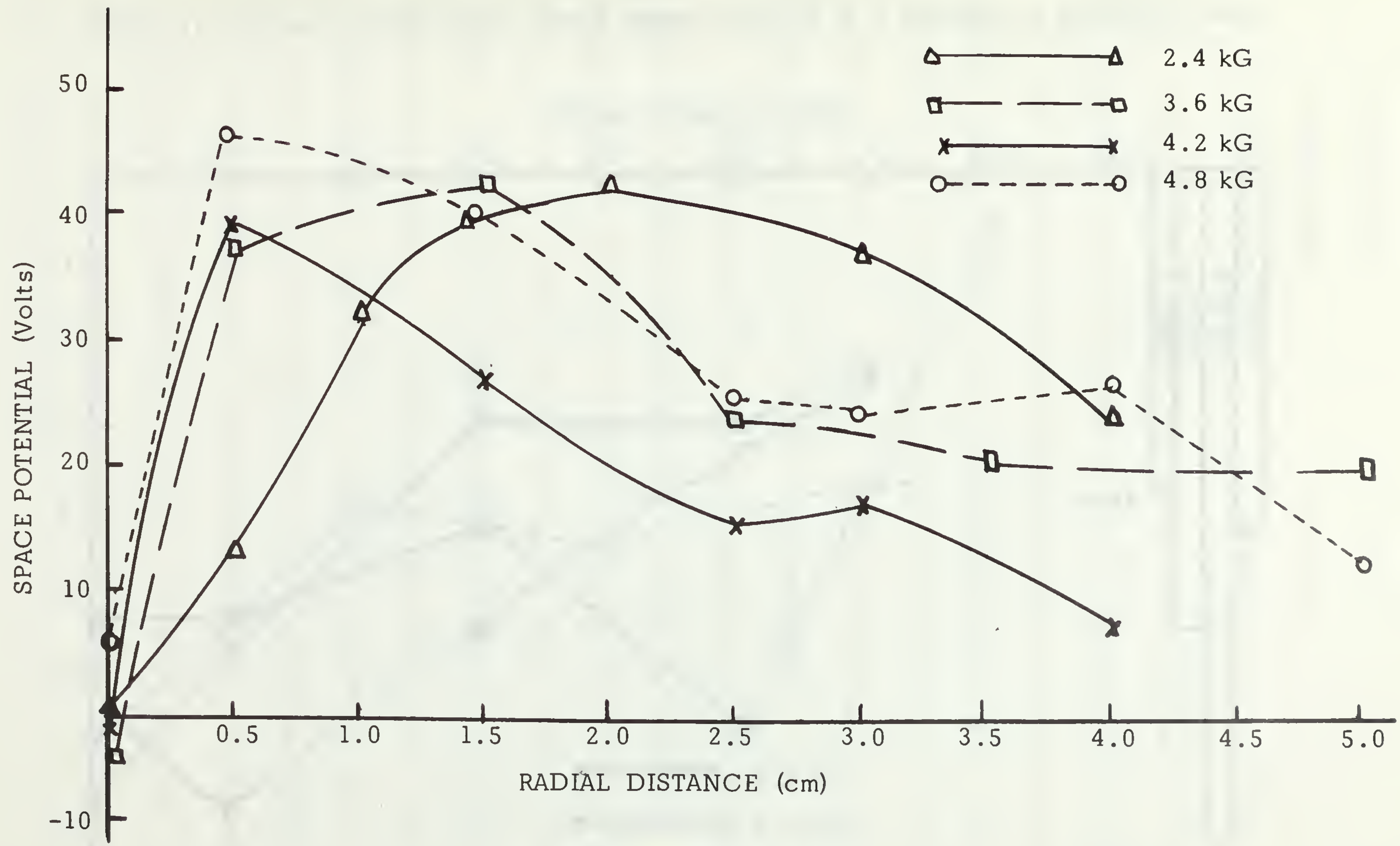


Figure 20. Space Potential versus Radial Distance as a Function of Magnetic Field

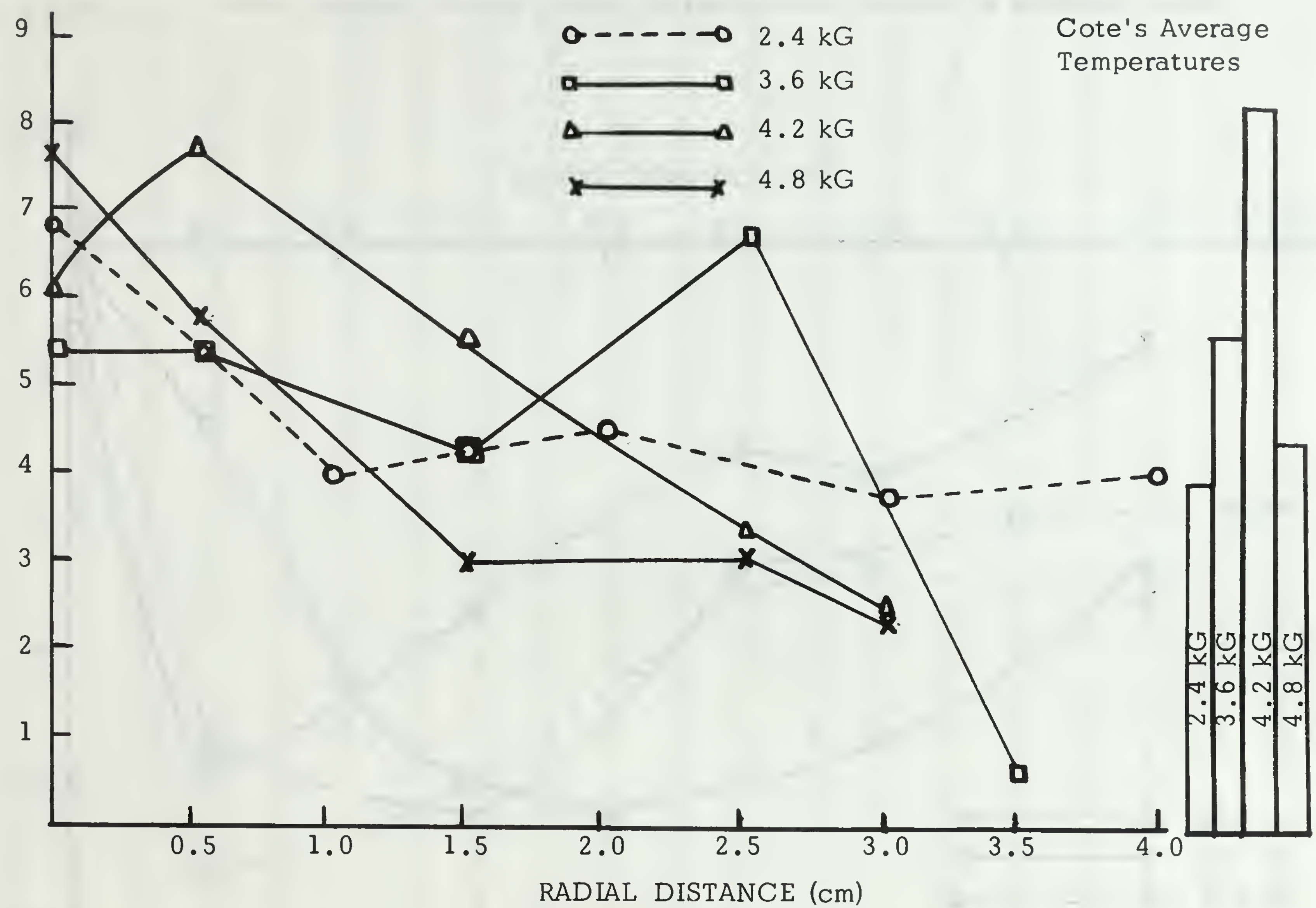


Figure 21. Electron Temperature versus Radial Position as a Function of Magnetic Field

T_e (2400 gauss)	4.0 eV
T_e (3600 gauss)	5.5 eV
T_e (4200 gauss)	8.1 eV
T_e (4800 gauss)	4.4 eV

These space-averaged electron temperatures are indicated by a bar graph adjacent to the space-resolved electron temperatures of Figure 21.

Both the spectroscopic and Langmuir probe techniques show an electron temperature peak at the 4200 gauss magnetic field. The experimentally obtained electron temperature distribution indicates the presence of an electron temperature gradient in the plasma column, the high electron temperature being at column center.

Gall and Oleson [7] conducted a study of a steady state argon plasma in a longitudinal magnetic field by means of cylindrical Langmuir probes. The Naval Postgraduate School plasma facility was used in the same configuration as the present study, minus recent changes, with a hollow cathode discharge serving as the plasma source. Electron temperatures as a function of radial position were determined in magnetic fields ranging from 600 gauss to 9000 gauss, and are shown in Figure 22. The argon and nitrogen electron temperature profiles are quite similar, with the argon column core temperatures being higher than the nitrogen temperatures. At the 1.0 cm radial position and outward, the electron temperatures have similar values, within experimental error, for both argon and nitrogen.

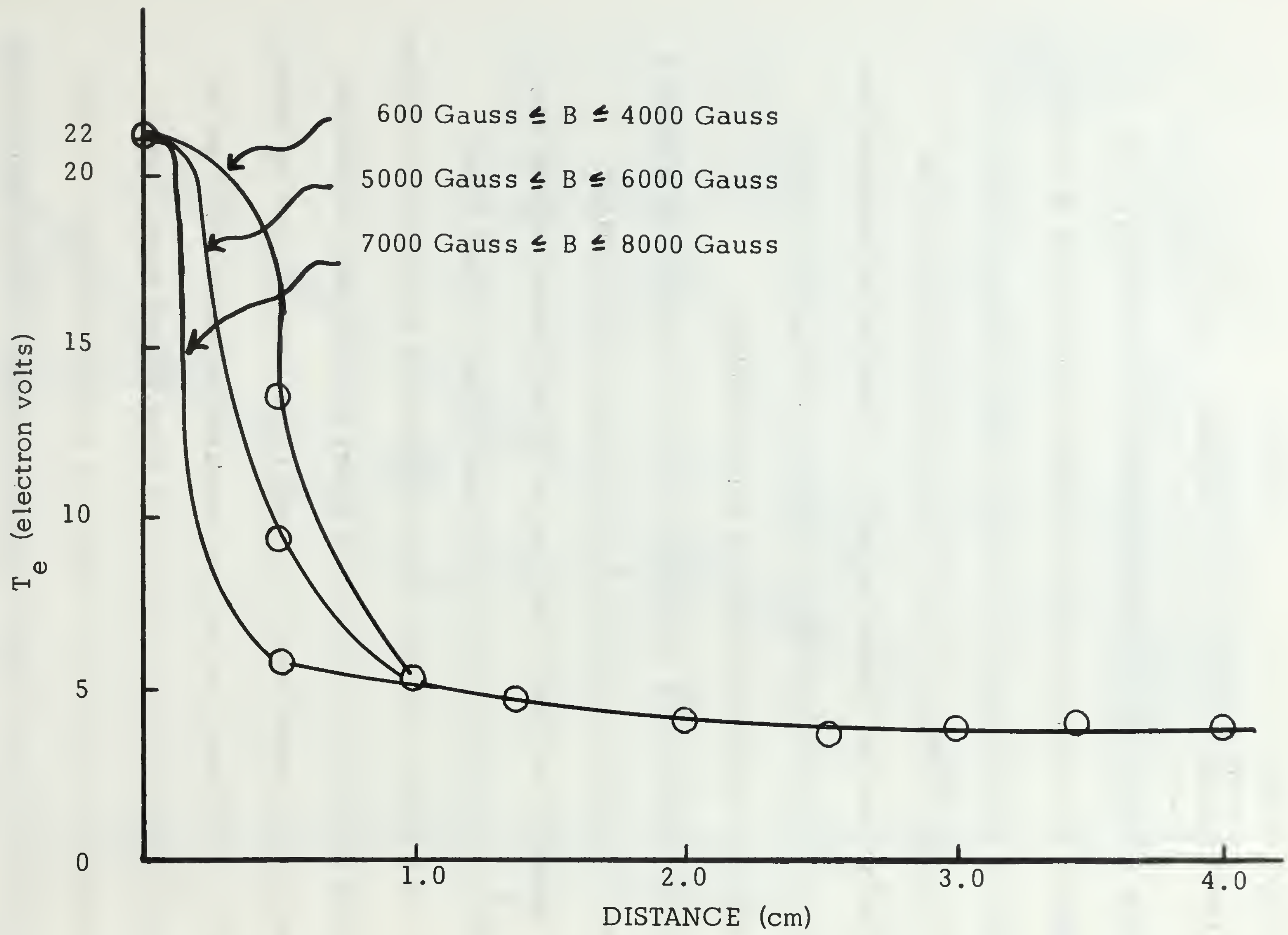


Figure 22. Electron Temperature versus Radial Position as a Function of Magnetic Field for Argon

D. INTERPRETATION OF RESULTS

1. Space Potential Study

The space potential study indicated the presence of a radial electric field directed toward the discharge centerline. As the rotational direction of the observed oscillation was in a right-handed direction with respect to the magnetic field, an $\vec{E} \times \vec{B}$ effect is strongly implicated in the propagation of the rotational fluctuation.

Representing the situation mathematically, the frequency of rotation can be described by the equation

$$f = \frac{v_o}{2\pi r} . \qquad (1)$$

Assuming the radial electric field observed to be perpendicular to the axial magnetic field, the classical solution to the motion of charged particles in such a crossed field situation yields a drift velocity perpendicular to the crossed fields in the $\vec{E}_r \times \vec{B}_o$ direction with a drift velocity

$$v_d = E_r / B_o \qquad (2)$$

which is charge sign-independent. The drift velocity would assume an azimuthal form in the case under examination. In effect

$$v_o = v_d \qquad (3)$$

Combining equations (1), (2), and (3) above,

$$f = \frac{E_r}{2\pi r B_o} . \qquad (4)$$

Equation 4 indicates an inverse proportionality of frequency to magnetic field, opposite to the experimental results. Offsetting the inverse proportion effect of the magnetic field is the radial electric field, which

increases with magnetic field. The nature of the reflex arc is of interest at this point. The plasma column core apparently retains the potential of the cathode, while as radial distance in the plasma column increases the anode assumes the role of end plate for the plasma column. The plasma column becomes a portion of the circuit between cathode and anode.

2. Plasma Column Current Flow

The space potential distribution would result in current flow, across magnetic field lines, from the maximum space potential region to column center. There would be no net current to the walls of the container as the insulated vacuum column walls could not continue to build up charge indefinitely. The proposed mechanism of current flow from the region of maximum space potential to column center is electron movement from column center to the region of large positive potential and hence to the anode. The cathode-anode current is considered to be the source of replenishment necessary for the steady state conditions achieved by the plasma column. No net current down the plasma column is noted. The higher electron temperatures at column center demonstrate high electron velocities at column center and add evidence in favor of a radial, cross-magnetic field current which the principles of thermal diffusion require. Exact calculation of this factor would involve knowledge of the distribution of the particle densities and energies, which have not yet been determined.

A cross-field current suggests the possibility of a $\vec{j} \times \vec{B}$ force, which will also be in a right-handed direction with respect to the longitudinal magnetic field. This force is examined by Jancel, et al, [8] in their discussion of the magnetohydrostatic equations. The magnetohydrostatic equations are obtained when the Maxwell equations

$$\nabla \times \vec{B} = 4\pi\vec{j} \quad \text{and} \quad \nabla \cdot B = 0$$

are added to the equations of plasma dynamics.

The plasma equation of motion in equilibrium configuration becomes

$$\nabla_r p = \vec{j} \times \vec{B} - \rho \nabla_r U$$

in which

p = pressure

B = magnetic induction

ρ = mass density

U = gravitational potential (negligible in magnetic field)

The pressure term represents the force on the plasma. A state of constant oscillation is achieved. This implies that the force described above is opposed in some manner. Neutral particle pressure and velocity-dependent diffusion rates are proposed as mechanisms limiting the particle motion resulting from the $\vec{j} \times \vec{B}$ force.

3. Reflex Arc Oscillation Sources

The $\vec{E} \times \vec{B}$ effect and the $\vec{j} \times \vec{B}$ force are proposed as the mechanisms by which the reflex arc plasma column reaches an oscillatory steady state condition. This theory agrees in part with that of Datlov, et al, [9] who conducted a study of the characteristics of a reflex discharge (P.I.G.) in hydrogen in a magnetic field. The dependence of the origin of low-frequency rotational fluctuation on the parameters of the discharge was studied. The radial profile of the plasma potential was measured with a heated probe. The fluctuation frequency was found to be approximately proportional to the drift velocity $v_d = \left(E_{radial}/B \text{ computed}\right)$ from the measured radial field and magnetic induction. The fluctuation frequency was found to increase with magnetic field, but the growth of the frequency was explained by the fact that E_r increased somewhat more than linearly with the magnetic field B.

In considering the results of Datlov with the results of this investigation, it is further proposed that the $\vec{E} \times \vec{B}$ effect mainly concerns the outer fluctuations and that the $\vec{j} \times \vec{B}$ force can be considered to be the primary effect involved with the inner oscillation. The linear dependence of the inner rotation frequency on magnetic field supports this proposal.

The positive column offers an interesting contrast to the reflex arc column. The literature contains many references to the screw instability of a positive column, the theory of Kadomtsev [10] being

among the more widely noted treatments of the subject. Hoh and associates [11, 12, 13] have contributed a number of important papers on the positive column. The key difference between the reflex arc and the positive column is the presence of a longitudinal electric field in the positive column. The instability mechanism is generally considered to be an off axis current filament drift which creates a charge separation, the ions assumed unaffected by the magnetic field lagging behind the rotation of the electron distribution. The space charge distribution in turn results in an $\vec{E}_\psi \times \vec{B}$ drift as illustrated in Figure 23. This drift tends to force the plasma column toward the container walls. The axial electric field tends to turn the electron screw around the tube axis. Because electric neutrality is to be maintained, the ion screw must rotate with the electron screw. The role the $\vec{j} \times \vec{B}$ force plays in the phenomena is not yet clear.

The mechanism for the reflex arc model, while employing an $\vec{E}_r \times \vec{B}$ drift, does not appear to incorporate the $\vec{E}_\psi \times \vec{B}$ drift in the observed fluctuation. The differing drift velocities at different radii in the plasma column do not appear to support the establishment of an $\vec{E}_\psi$ electric field.

4. Modification of Plasma Characteristics and Parameters

The recent modification of the plasma facility created no apparent changes in the plasma characteristics.

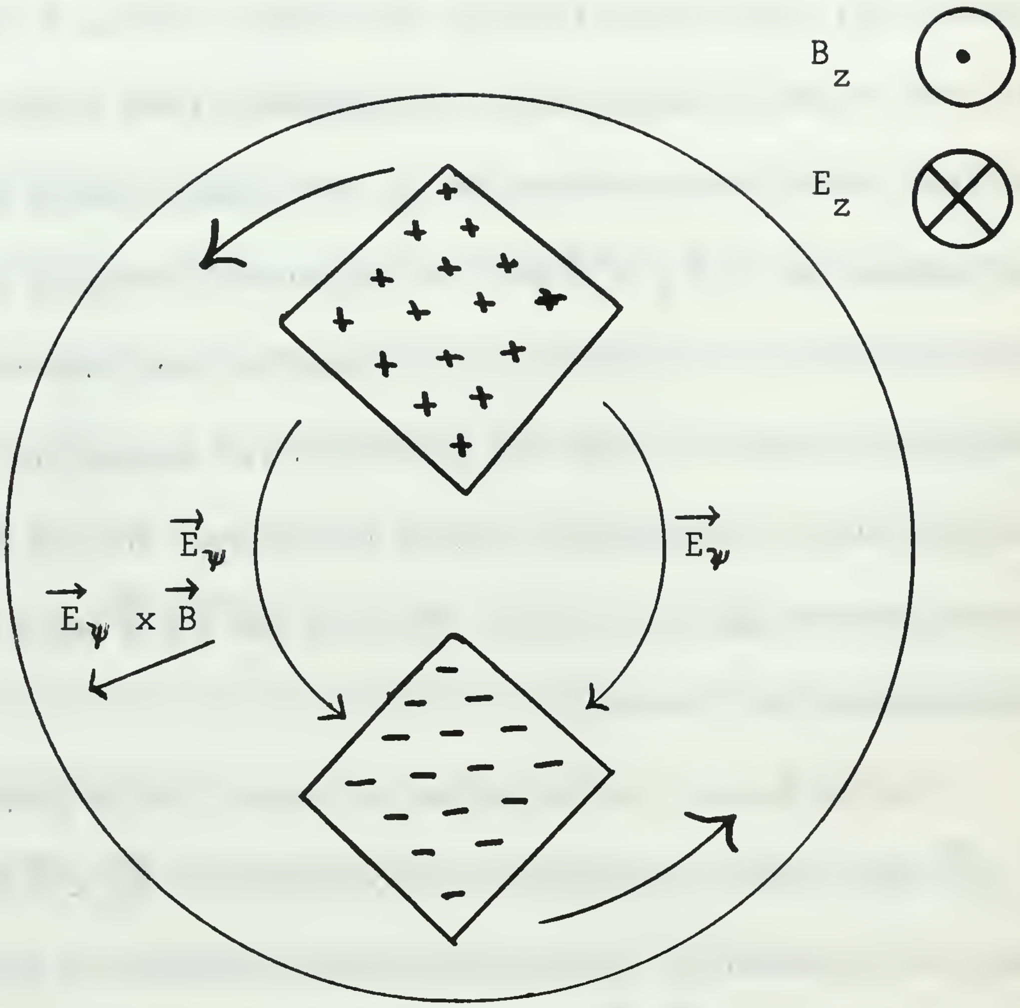


Figure 23. A Cross-sectional View of Space Charge Distribution Responsible for Screw Instability of Positive Column

E. RECOMMENDATIONS

1. 60 Hz - 360 Hz Oscillation

The feasibility of design of a feedback system to suppress the 60 Hz - 360 Hz fluctuations should be examined. The most probable employment of such a device would be to modulate the anode voltage supply so as to suppress the 60 Hz - 360 Hz oscillation imposed on the plasma column by both the cathode-anode complex and the magnet system.

2. Rotational Fluctuations

The reflex arc plasma column should be examined for an onset and cut-off of the rotational oscillations and, if found, a study of plasma parameters in the vicinity of these magnetic fields should be conducted with the objective of establishing the conditions which lead to the onset of fluctuation and the continued propagation of the fluctuations. A study of plasma parameters using plasmas of other elements may prove beneficial in establishing the causes of rotational modes. The role of the anode in the propagation of the fluctuations should be investigated by varying the anode parameters. Possible areas of investigation could include anode configuration and the effects of shielding the anode from the plasma column.

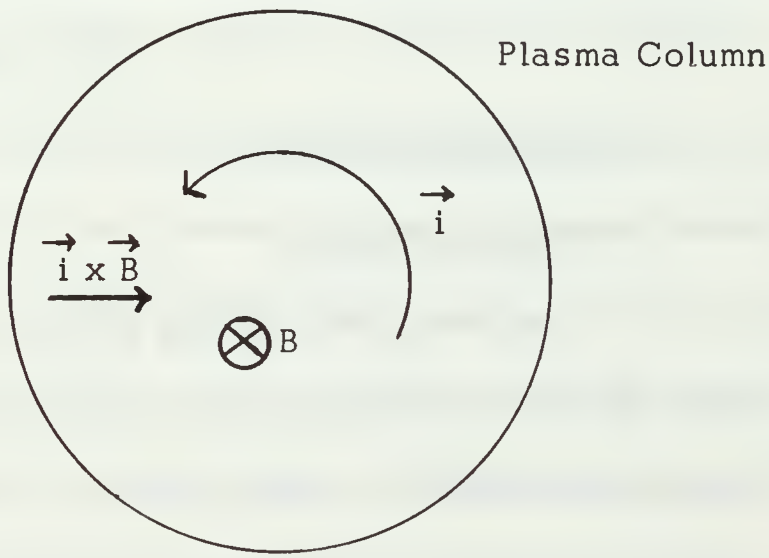
IV. THETA PINCH PERTURBATIONS

A. BACKGROUND

One of the devices that has been considered for possible use in a thermonuclear reactor has been the plasma pinch. The theta pinch device installed in the plasma facility is designed to compress a portion of the plasma column by a sudden increase of longitudinal magnetic field. This field increase is caused by a current pulse on the copper conducting ring around the plasma column. The column compression results in a small volume of high temperature, high density plasma. The pinch effect enjoys only a brief existence due to a rapid breakup once the pulsed magnetic field is removed. As noted by Rose and Clark [14], the imploding magnetic wall consists of B_z lines of induction, the z-axis being the longitudinal axis of the vacuum column. The increasing B_z in turn induces a current i around the plasma column. Operational aspects of the device are illustrated in Figure 24.

The installation of the theta pinch device was completed just prior to the completion of the period available for research. The device was tested with nitrogen gas in the plasma system. At pressures ranging from 0.5 microns to 80 microns, activation of the theta pinch device produced ionization in the nitrogen gas and propagation of an ionizing front down the pyrex column. These effects were visually observed.

Side View - Magnetic Induction Increases



End View: A. Increasing Magnetic Field induced i to counter rise in field.

B. $\vec{i} \times \vec{B}$ force exerts pressure on column, compressing column.

Figure 24. Theta Pinch Operation

B. REFLEX ARC NITROGEN PLASMA

Attempts to observe the effects of the theta pinch operation on the reflex arc nitrogen plasma in a 1300 gauss magnetic field were at first unsuccessful. Photomultiplier tubes aligned on the plasma column and probes within the column both failed to register a noticeable change in the plasma characteristics. Upon each theta pinch discharge a great deal of electric noise was registered by both the electric probe and the photomultiplier tube circuitry. This effect could have hidden the theta pinch effect on the plasma column, but if such effects were present, they would have been quite small compared to the normal plasma activity. Recent studies by plasma laboratory personnel have shown the presence of plasma perturbation. Further studies are in progress.

C. RECOMMENDATIONS

1. Plasma Facility

The theta pinch device should be modified to produce a greater pinch effect by the addition of a larger capacitor bank. Various plasma facility parameters, to include magnetic fields and neutral gas pressure, should be adjusted in the search for the effects of the theta pinch device, and an effort should be made to reduce plasma fluctuation.

2. Measuring Devices

Probe and photomultiplier tube circuitry must be redesigned with shielding from the electric noise of the theta pinch device being of primary consideration. The use of light pipes should be investigated as an aid to removing the photomultiplier circuitry from the vicinity of the electric disturbances.

V. SUMMARY

The use of cylindrical Langmuir probes in a reflex arc, magnetically confined nitrogen plasma confirmed the presence of fluctuation in the plasma column. The fluctuations were identified as being a 60 Hz - 360 Hz oscillation imposed by the power supply to the plasma facility, and two rotating fluctuations present in the outer and inner zones of the plasma column.

Analysis of electric signals and the characteristic curves of the Langmuir probes had the following results:

1. The 60 Hz - 360 Hz oscillation was found to be a characteristic of the plasma column as a whole with no wave propagation down the plasma column being noted.

2. The inner and outer rotational fluctuations were shown to be in a right-handed direction with respect to the longitudinal magnetic field.

3. The space potential profile of the plasma column appeared to resemble a gaussian distribution with the column center at zero volts amplitude and the point of maximum space potential moving toward column center as the longitudinal magnetic field was increased.

4. The electron temperature distribution profile also resembles a gaussian distribution with the maximum temperature located at column center and the electron temperature decreasing with radius.

The direction of rotation, space potential distribution, and electron temperature profile lend credence to the hypothesis that an $\vec{E} \times \vec{B}$ drift effect and a $\vec{j} \times \vec{B}$ force are responsible for the rotational fluctuation propagation.

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13. ABSTRACT

A reflex arc nitrogen plasma in a longitudinal magnetic field has been investigated by means of cylindrical Langmuir probes. Magnetic fields varying from 2400 gauss to 6600 gauss were studied. A radial profile of electron temperature and space potential was obtained as an aid to understanding the inner and outer rotational fluctuations previously noted to be characteristic of the reflex arc column. The effect of crossed magnetic and electric fields resulting in $\vec{E} \times \vec{B}$ particle drift has been proposed as the primary mechanism of the outer rotational fluctuation, while the inner rotation mechanism has been proposed to be the $\vec{j} \times \vec{B}$ force of the magnetohydrostatic equation of a plasma in equilibrium. Diagnostic measurements of a theta pinch device on the plasma column were not successful due to circuit pick-up of electric signals due to the theta pinch current pulse.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plasma						
Oscillation						
Reflex arc plasma						